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Underwater inspection of steel offshore installations: implementation of a new approach

FINAL REPORT TO CONTRIBUTORS
JUNE 1989

Foreword

The project leading to this report was undertaken by UEG using technical services contractors for each of the seven studies directed at meeting the overall objectives. The studies and their contractors are given in Section 1.3. During the course of the work the UEG Project Managers were R.J. Simpson, R.K. Venables and R.W. Barrett.

The project was funded by the following participants:

American Bureau of Shipping
Britoil Plc
British Gas Plc
BUE Group
Comex Houlder Ltd
Conoco (UK) Ltd
The Department of Energy (UK)
Det norske Veritas
Earl & Wright Ltd
Elf UK Plc
Exxon Production Research Company
Harwell Laboratory
McAlpine Sea Services Ltd
Marathon Oil Company
Maersk Olie og Gas A/S
Minerals Management Service, US Department of the Interior
Norwegian Petroleum Directorate
OSEL Group
Petroleo Brasileiro S.A.
Phillips Petroleum Company UK Ltd
SonSub Services Ltd (formerly Sonat Subsea)
Joint Swedish Group
US Coast Guard
Wimpey Offshore

A Steering Group, comprising representatives of participants, UEG and the technical services contractors, provided the forum for discussion and commented on this report prior to publication. During the course of the project the Steering Group comprised:

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Mr. R.K. Venables	Steering Group Chairman and Project Manager (to Dec 87)
Mr. R.W. Barrett	Steering Group Chairman and Project Manager to completion

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Summary

This report is the outcome of a major joint industry sponsored project initiated by UEG. Its overall aim is to improve the effectiveness of underwater inspection of offshore installations, particularly through the use of a more rational method of planning inspection operations. The heart of this method is that that an installation owner should be provided with a level of confidence in the condition of each component of the installation commensurate with the consequences of failure of that component.

After an introductory Part which outlines this method and sets it in the context of other inspection planning philosophies, major chapters of a second Part review and discuss:

- types of damage and deterioration
- applying the proposed inspection planning method to existing installations
- the management of inspection operations offshore
- inspection operations – including inspection methods, cleaning, intervention and monitoring
- the assessment of any damage found.

A final Part discusses the adaptation of the proposed planning method to the design of new installations, and suggests how attention to detail design of new structures can ease the practical tasks of underwater inspectors in future.

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1.1 BACKGROUND TO THE PROJECT

Underwater inspection and defect assessment are of great concern to all involved in ensuring the long-term integrity of offshore installations. Over the years since first gas and then oil were developed from North Sea fields, the offshore industry has made substantial technical progress and gained considerable experience of structural inspection under water and of defect assessment.

The industry drew on experience gained on offshore installations elsewhere in the world but, as in many other facets of North Sea operations, the harsh environment there has led to stringent inspection requirements and associated technical advances. The industry has also drawn on the considerable research and experience of non-destructive testing and defect assessment in the nuclear and aircraft industries.

And yet, despite these advances, it was clear that many questions – some of fundamental importance to improving the effectiveness of underwater inspection – remained:

- What items should be inspected and how often?
- Will defects be recognised when they are 'seen'?
- How are the items to be inspected to be selected?
- What is the smallest detectable defect?
- How frequently should we inspect?
- How does the design, and particularly the estimated fatigue life of particular structural elements, affect the need for, and the objective, nature and frequency of any inspection.
- What type and size of defect is sufficiently small not to jeopardise the continued safety of an installation?
- What is the significance of a given defect in a given position?
- How does the underwater environment affect the feasibility, accuracy and frequency of any inspection?

UEG has, since the start of its work on offshore structures, been actively involved in many aspects of in-service performance of installations. In 1978, still the 'early days' of North Sea development, UEG published its Report UR10 'Underwater inspection of offshore installations: guidance to designers'[1.1] which addressed and provided recommendations on actions which designers could take to ease and reduce the underwater inspection of the installations they design. Its recommendations remain remarkably pertinent today.

Whereas UR10 concentrated on design detailing, this project addressed broader issues of philosophy behind inspection planning and how a new approach could be brought to inspection of existing structures as well as to the design of new structures.

With that background, UEG set up the project which has led to this report. The aims were:

- to provide a forum for offshore industry representatives to discuss and develop a cogent philosophy for the underwater inspection of offshore installations and pipelines
- to prepare detailed practical guidance to match the results of the first objective.

1.2 SCOPE AND LIMITATIONS

The ensuing project was targetted at the underwater inspection of installations world-wide, drawing on the extensive experience already gained in the major offshore oil and gas production areas. It was aimed to cover all types of installations, and concrete platforms were the subject of one of the studies within the project – see Section 1.3.

This report, however, concentrates on providing analysis, a new approach and practical guidance on the underwater inspection of steel offshore installations. The majority of the report concentrates on fixed structures, with relevant comments added on the special considerations for some other kinds of installations. Within the studies related to steel structures, advice was sought on aspects of inspection appropriate to different types of installations as follows:

- fixed steel tubular structures
- floating structures moored long term on station
- tethered buoyant platforms
- production risers, fixed and compliant
- pipelines
- subsea installations.

The project was undertaken by UEG using technical services contractors for seven studies – see Section 1.3. The project was funded by a group of interested organisations, including oil companies, governments, contractors, designers, suppliers and a certifying authority.

A Steering Group comprising contributors' representatives, UEG staff and representatives of the technical services contractors provided the forum for discussion and commented on this report prior to its circulation to contributors. UEG were project managers and provided the Chairman of the Steering Group.

1.3 STUDIES WITHIN THE PROJECT

Several studies have been undertaken within the project, all directed towards meeting the overall objectives and the preparation of this and other reports. The seven studies and their technical services contractors were:

Study One: Methods of underwater inspection and intervention for steel structures and subsea installations – Inspection Integrity Quest Partners

Study Two: Interaction between design and inspection of steel structures – Earl & Wright Ltd

Study Three: Inspection of concrete structures – McAlpine Offshore Ltd

Study Four: Damage assessment – Wimpey Offshore Engineers and Constructors Ltd

Study Five: Management of resources and manpower planning – Thalassa Advanced Technologies Ltd

Study Six: Significance and inspection of marine fouling – Aberdeen University Marine Studies Ltd

Study Seven: The potential for probabilistic methods in underwater inspection – A/S Veritas Research.

Apart from the individual study contractors, considerable additional input was provided by Mr J de Prey of UEG in preparing Chapter 6.

Reviews and appraisals of various chapters were undertaken by Mr R D Allen of ATOM and Mr J Bevan of Submex Ltd.

The whole report was technically edited and prepared for printing by Mr M J Wright of Techword Services.

1.4 LAYOUT OF THIS PROJECT REPORT

This report is presented in three distinct but complementary parts:

- *Part A: The need for change and the basis of a new approach* – is aimed at all readers interested in improving the effectiveness of underwater inspection. It reviews the motivations behind inspection planning appropriate to different structures and circumstances, reviews current practice (and its limitations), analyses the need for a more rational approach and a number of alternatives, and finally presents the basis of a new, more rational approach to inspection planning.
- *Part B: Effective implementation* – reviews damage and deterioration, provides practical guidance in the management of inspection (including implementation of the new approach to inspection planning outlined in Part A), provides practical guidance on inspection and monitoring operations, including inspection methods, cleaning, intervention methods and monitoring, and concludes with a major section on the assessment of damage.
- *Part C: Interaction between design and inspection* – discusses the adaptation of the principles developed in Part B to the design of new structures. Aspects of design detailing to ease the practical tasks of inspection are also addressed.

Part A

The need for change and the basis of a new approach

2 Underwater inspection in context

2.1 WHY INSPECT?

2.1.1 Overall objectives

Almost all operators of offshore installations carry out some underwater inspection each year. The size of the installation and the short weather window in which diving can be carried out safely are two of the factors which may govern the amount of inspection undertaken each year. But why is underwater inspection undertaken at all?

At the simplest level it can be argued that underwater inspection is undertaken to confirm the integrity of parts of the structure which are normally hidden from view. Implicit in this argument is the assumption that loss of integrity automatically has some significant consequence, yet it is well known that some offshore installations, such as steel jacket structures, are highly tolerant of defects.

In this document, the following general statement will be adopted as the starting point for justifying the rationale for any inspection philosophy selected:

> "The ultimate objective of an inspection plan is to provide a level of confidence in the condition of each component (of an installation) commensurate with the consequences of failure of that component."

Chapter 3 attempts to develop a new approach to underwater inspection based on this fundamental logic, but first it is appropriate to consider the possible consequences of component failure.

2.1.2 Consequences of failure

The way in which loss of individual components can lead to breakdown of all or part of a critical system is outside the scope of this section. In some instances, failure of a component may have no immediate effect; in other cases – such as a crack in a main oil riser – the consequences will be immediate, obvious and serious. The following list covers some of the considerations typically reviewed by operators when forming an overall strategy:

1. *Protection of life*
   In many instances, a work crew is housed on the deck of an offshore installation which is 'live'. A major structural failure will have obvious implications. Also to be taken into account may be the lives of those on adjacent installations, work boats or accommodation vessels. Loss of life may also result from failure of an underwater hydrocarbon system due to ignition at the water surface.
2. *Assurance of economic production*
   This is a major consideration for operators as offshore running costs are largely independent of rate of production. If production has to be suspended due to uncertainty of the integrity of a critical system, operation of the installation is esentially uneconomic until the uncertainty has been satisfactorily resolved. Loss of part or all of the installation necessarily also has capital cost implications as well as lost revenue consequences.
3. *Protection of environment*
   Although pollution is most obviously associated with the risk of oil spillage, operators of offshore installations also have a responsibility (statutory in some instances) to remove their installations on completion of operations. (Implicit in this requirement is the necessity to maintain the fabric of the installation to a level where decommissioning and removal can be undertaken safely and cost-effectively.)
4. *Statutory requirements*
   Although the consequences of failure are only indirectly linked with the requirements of statutory bodies and their certifying authorities, the latter may be empowered to halt production if they consider it necessary on safety grounds. The certifying authorities play an important role in ensuring that inspection is treated in a responsible manner and this topic is treated separately in Section 2.2 below.

It can be seen that the ultimate reasons for inspection are a combination of financial and safety considerations. In general, the operator has an interest in all the items listed above, whereas the statutory and certification bodies have a primary interest in safety and pollution control and can be considered to act in the general interest of the nations they serve.

2.2 STATUTORY REQUIREMENTS

Some national governments responsible for the exporation and exploitation of mineral resources within their territorial limits have developed statutory requirements/regulations providing a framework for the survey of offshore installations. How these requirements are enforced, ie by the governing state or through delegation by agency agreements, depends upon local government practices. For example, in the UK, the responsibility for survey and issue of certificates of fitness is delegated to the Certifying Authorities appointed by the Secretary of State for Energy. It is the responsibility of the installation owner to contract the services of one of these appointed Certifying Authorities. Operational requirements of some other countries are given in Appendix 1. The scheme for re-certification of the subsea portion of offshore installations in the UK is based upon a 5-year cycle which is the maximum period of validity of a Certificate of Fitness (this is limited to 4 years in Norwegian waters).

The UK regulations relate to *annual* and *major* surveys, but these are generally defined with an alternative system as follows:

- The *annual* survey requirement, which is designed to ensure that any deterioration of the structure is within acceptable limits, should include a close visual inspection down to and including the splash zone (or waterline at maximum freeboard as appropriate) and to detect obvious damage and indicate areas likely to warrant further investigation. In addition, a survey should be undertaken of any repair or scour prevention work since the last survey. An assessment of marine growth is also required.
- The *second annual survey after each major survey* should include a general inspection of major parts of the installation below the splash zone.
- The *major survey* (usually the 5th year) includes the requirement of an annual survey and comprises a general examination under water together with a close visual examination (with cleaning) of selected welds, as agreed with the Certifying Authority, and a determination of platformsettlement/tilt (air gap).
- *Alternatively* the UK regulations allow the Certifying Authority to accept, in lieu of a major survey, a series of continuous surveys conducted in rotation with the annual surveys, provided the results obtained are equivalent to a major survey.

The objective of the new approach to the planning of underwater inspection outlined in Chapter 3 and described in more detail in Chapter 5 is to establish a rational basis on which to satisfy the need for further detailed (underwater) inspections and/or NDE based upon performance. In particular, the new approach suggests a rational basis for identifying the areas to be subjected to detailed inspection.

2.3 TYPES OF DAMAGE AND DETERIORATION

Offshore installations can sustain some damage or deterioration before their local or overall structural integrity is threatened. The limiting amount of damage varies, depending on the type of damage or deterioration and its location, and some types of structure (eg steel jacket structures) are more tolerant of local damage than others. Different types of damage are outlined below, emphasising how they affect the development of a rational inspection programme.

Damage to offshore installations falls broadly into two categories:

- *Progressive damage*, where the severity of the damage may at first be too slight to be detected but, if left unchecked, may grow to cause local or total structural failure. The two types of damage in this category of relevance to offshore structures are fatigue cracks and corrosion. Fatigue cracks may be present, but too small to be detected either visually or by NDT during one inspection; a critical problem for inspection engineers is that they may grow to such a size as to threaten the stability of a component before the next routine inspection. Similarly, some corrosion can be tolerated in a properly designed marine structure, but only up to limits where first its serviceability and then its ultimate structural integrity are compromised.
- *Instantaneous damage*, where a single event causes immediate damage such as tearing, denting, gouging or buckling which may lead to immediate failure in the form

of fracture, member collapse or joint collapse. The structure is not likely to show any signs of distress before the instantaneous damage occurs but the event causing the damage will almost certainly have been reported so that non-routine inspection can be carried out to discover possible damage.

There is inevitably some interaction between these two damage types. For example, fatigue damage may grow in a predictable, progressive manner until a stability limit is reached where subsequent extreme environmental loading may cause instantaneous fracture collapse. Or, load redistributions following accidental (instantaneous) damage to one or more members may alter the rate at which fatigue cracks grow at nearby joints.

The most common causes of structural damage and deterioration are:

- *Shortcomings in design,* such as inaccurate estimations of wave loadings, hot-spot stresses or material fatigue properties. Design detail errors such as not allowing sufficient access for proper fabrication can also lead to later deterioration via the 'construction deficiencies' route (see below).
- *Construction deficiencies,* such as faulty weldments, undercuts and alignments outside tolerances.
- *Accidental events,* such as supply boat collisions and dropped objects.

Although not in the same category as the structural damage and deterioration described above, marine fouling is a form of deterioration that directly affects the stability of the structure and the way in which structural inspections are carried out. The fouling obscures the surface of an installation and must be removed before surfaces can be inspected for fatigue cracks. It also adds to the hydrodynamic and static loading on the structure and it may accelerate some forms of corrosion and cause physical damage to steel surfaces. As part of any structural inspection, it is necessary to survey the extent of marine fouling and to remove it in critical areas.

The subject of damage and deterioration to offshore installations is dealt with in more detail in Chapter 4.

2.4 LEVELS OF INSPECTION

2.4.1 Appropriate levels of inspection

The quality of inspection at a given underwater location is governed by:

- technical constraints
- time
- cost.

A wide range of technical issues must be taken into consideration. These include not only the practical issues of inspection (such as access, reliability of techniques, underwater visibility) but also the ability to understand and interpret inspection findings correctly. A reliable method of inspection data storage and retrieval is also necessary.

Some parts of an installation are much more critical than others in terms of requirements for inspection and Chapter 3 concentrates on the development of a rationale taking the relevant constraints into account. But it is appropriate to note here that there are two basic categories which will appear in inspection records:

- *Undamaged components*
  This category includes all components in which damage has not yet been detected by inspection.
- *Damaged components*
  This category includes all components for which damage has been detected during previous inspections.

The first of these categories implies that there is a period in which damage can exist and yet remain undetected. This can be due to one of three causes: damage occurring to a component between inspections, damage occurring at a site not identified as requiring inspection (or, not yet inspected), and failure to identify damage during inspection.

In deciding on appropriate levels of inspection, this category is of primary importance. Firstly, a knowledge of the importance of each component to the integrity of the overall installation is required. Secondly, it is important to understand the limitations of the inspection techniques used.

It should be noted that the importance of individual components can only be deduced from theoretical models. In the case of non-redundant components (such as risers) the criticality can easily be evaluated, but for highly redundant installations (particularly steel jacket structures) the assessment of the importance of individual components is more complex. The assumptions made in modelling may themselves be suspect and so a practical inspection plan should include the inspection of a representative proportion of the components not highlighted as critical by theoretical modelling. This can be achieved by applying detailed NDT inspections to such components and/or by using global inspection techniques (eg flooded member detection) and rapid screening methods for damage detection. On finding any structural defects through these screening techniques, detailed NDT can then be directed to the area in question.

Where damage is known to exist in a component, future inspection can be tailored to suit both the importance of the component to the overall installation and the theoretical predictions of the defect's progress to failure.

2.4.2 Monitoring continuing performance

The integrity of components can be evaluated by either periodic or continuous monitoring. Both forms are in common use.

Discrete monitoring, usually referred to simply as 'inspection', includes visual inspection and non-destructive testing and is so categorised because the component is only monitored periodically. For components of moderate importance, the period between inspections may be of the order of 4–5 years, assuming no damage is detected. This is by far the most commonly used – and important – classification of monitoring, as detailed information can be obtained from a specific area of interest.

Continuous monitoring implies that the health of a component is constantly appraised; a fail-safe 'flooded member detector' device linked to a central monitoring station on the deck of the installation would be an example. Another form of continuous assessment which has been applied offshore is vibration monitoring, in which the frequency response of the structure as a whole is constantly measured; changes highlight the possibility of fracture. Acoustic emission systems are also used for continuous monitoring. Continuous assessment techniques have not been used extensively as a form of ensuring continuing integrity. This is because their sensitivity has been found to be inadequate and there are also reliability difficulties.

The uses of the various techniques, and the constraints upon their reliabilities and usage, are discussed in Chapter 7 of this document.

2.4.3 Assessing the integrity of damaged structures

When damage is discovered by inspection, a critical appraisal of the consequences – both immediate and future – is undertaken. Powerful theoretical techniques are now available (described in Chapter 8) to help interpret the significance of damage[eg 2.1, 2.2 and 2.3]. In many cases, it may be possible to demonstrate that no remedial action is necessary, either immediately or at all. But, unless good quality information on the extent of damage is available, the theoretical techniques are in danger of yielding wrong conclusions. At worst, it may be concluded that a component is in a stable condition when in fact it is on the verge of failure. At the other extreme, poor information may enforce conservative assumptions to be made during the theoretical assessment, leading to a decision to execute an expensive – possibly unnecessary – repair.

The assessment of damage at the inspection site is therefore critical. Fortunately, once a defect site is located, the cost of obtaining more detailed information is considerably lower than the costs associated with locating the damage in the first instance. However, good communication between the on-site inspection team and those who will conduct the damage assessment is vital if the right additional information is to be gathered. The importance of accurate 'defect characteristion' cannot be overstressed. The approach to be adopted is described more fully in later Sections.

2.5 CURRENT PRACTICE IN THE PLANNING OF INSPECTION

2.5.1 Introduction

As part of Studies 2 and 4 of the Project leading to this document (see Section 1.3), operators and others engaged in North Sea work were asked to give details of the methods currently used by them in the planning of underwater inspection. A summary of their views is presented below. It should be appreciated that, whilst the summary is presented here as objectively as possible, it is based on the subjective opinions of invididuals within different organisations. Differences of approach were even noted between different parts of the same organisation.

The primary objective of inspection was almost always seen to be to ensure the continuing fitness for purpose of the installation, and not merely to confirm compliance with statutory requirements. To this end, most inspection programmes involve a greater effort than the minimum called for.

2.5.2 Fixed platforms

Inspection of the members (rather than the joints) of fixed steel installations is aimed at identifying only major damage, such as denting from dropped objects. Since this can be achieved by visual means using divers or remotely operated vehicles (ROVs) at relatively low cost, most operators aim to look at all primary members at each annual survey. Members containing fabrication features such as manhole closures usually receive a greater proportion of inspection time.

Much more inspection effort is directed to the structural joints, where fatigue damage may manifest itself in the form of cracks propagating from points of high stress. Commonly, marine growth would effectively conceal all except full or partial severance. Any visual or other inspection for cracks therefore requires considerable diver time to remove marine growth, and it is practical only to examine a small sample of all the joints each year. Nearly all the operators questioned stated that their total inspection samples over the inspection period between major surveys (5 years in the UK sector) were approximately 10% of all saddle welds. A distinction is drawn here between joints and saddle welds, in that a joint comprises a number of branch members welded to a chord or through member. The relative size of the inspection sample therefore varies from one installation to another, but is typically in the range of 25 to 50 welds between major surveys. This percentage is only intended as an indication of current levels of inspection, and should not be interpreted as a guideline for the formulation of acceptable inspection samples. The prevailing philosophy is one of flexibility based on sound engineering, and there is a mutual understanding of needs between the ceritfying authorities and the operators.

A criterion or criteria are necessary to select the sample, and all operators interviewed used fatigue design life as the criterion. Half of the operators also consider the criticality of the joint to structural integrity and a smaller proportion still also take stress levels and fabrication details into account.

An S-N fatigue analysis of a computer-based structural model is used to calculate fatigue design lives. One operator starts on the basis that joints should be inspected every 25% of their calculated fatigue lives but the selection is more subjective in practice, with human factors, contingency inspections, budget and time of year all having a big influence. One operator incorporates redundancy analysis for setting part of the inspection programme; those joints with a short fatigue life and a major consequence should they fail have a high priority in the inspection list. The general impression is that most of the operators still use S–N fatigue analysis as the basis for inspection planning but are beginning to turn to redundancy analysis as an aid to concentrate efforts on the most critical areas. One operator with new structures with long design lives uses the first 5-year re-certification term to cover most of the structure with a detailed visual inspection so as to establish a base line for future inspections. His future inspection programmes will then be based on fatigue, redundancy analysis and the findings from the 5-year baseline results.

In the event of a defect being detected or an area of a structure being of particular concern, all the operators would place these as a high priority. Two of the operators would increase their inspection efforts in these areas outside their normal inspection programme. One operator would modify the inspection programme so that sensitive areas would be examined every year.

All but one of the operators surveyed would carry out detailed analysis of any damage found, to aid in deciding the course of action. The analysis is not restricted to defect assessment to predict the course to failure but is aimed at understanding the nature and cause of the defect. This is particularly important to one operator who uses this information to update the computer models of his structures and to help plan future inspections by identifying similar areas to that in which the defect has been discovered.

The methods most widely used to detect cracks are magnetic particle inspection (MPI), flooded member detection and visual inspection. Operators do not agree about the reliability of detection; some claim they can find surface defects of 10 mm length or less with a 'reasonable degree of reliability'. They are aware that reliability is dependent on the human factor and varies between divers. The operator with new structures looks for cracks using a 'broad brush' approach. He concentrates on flooded member detection, covering all primary and secondary members (none of which are expected to be damaged) during the first five years for the equivalent cost and overall reliability of detailed NDT inspection of five welded joints per year. This operator believes that the detailed inspection techniques, while potentially offering a higher degree of sensitivity, have such a reduced reliability both in terms of operator capability and in structural coverage that they are not cost-effective during the first five years of a structure's life. He also believes that these techniques require a lot of experience and knowledge to ensure that reliable and sensitive readings are maintained – they should not be used in the field until comprehensive, documented, internal trials have been carried out.

Such confidence in flooded member detection is not universal amongst offshore operators, but for appropriately designed structures, it seems to be a promising technique.

No matter what method is used to search for cracks, a general visual inspection is also carried out each year which typically includes:

- the condition of the corrosion protection system
- the marine growth profile
- the condition of risers, J-tubes and caissons, together with their supports
- the condition of conductor casings
- a check on the amount of foundation scour and debris accumulation
- a visual examination of structural members and appurtenances in and above the splash zone
- a check on the security of bolted appurtenances.

In addition, general inspection is likely to include ultrasonic thickness measurement of selected components and measurement of the cathodic protection current density and/or potential.

2.5.3 Floating installations

Although floating installations do not possess the same degree of inherent redundancy as fixed structures, they are more easily inspected if, by dry-docking or de-ballasting, some 'underwater' inspections can be done in the dry (the installation must be taken out of service for this purpose). Typically, floating installations have far fewer structural members and joints than fixed platforms, and these are all accessible to some degree for internal inspection (although internal inspection alone is considered inadequate as external defects may then pass undetected). Unlike the inspection programmes for many fixed installations, the programmes for most floating units are generally arranged to feed information back to designers.

Detailed inspections are usually carried out every four years of the installation's service life. Less-thorough inspections are conducted annually within the four-year cycle. The detailed inspections include:

- checking all critical joints for cracks using approved NDT techniques ('critical joints' are specified on calculated fatigue life and past performance of the joint)
- visual inspection of other joints and structural members
- thickness-gauging of columns, braces, hulls and ballast tanks
- external visual inspection of hulls below the light draft waterline by divers
- checking the condition of paint and cathodic protection systems.

An annual-inspection manual is produced by the designer of a floating installation; it describes the inspection requirements of the unit and includes:

- the scope of the inspection, and instructions for its preparation, execution, and reporting
- a description of the unit, including reference systems and an index of as-built drawings
- schedule of joints and members to be inspected, including details of frequency of inspection and type(s) of NDT to be used
- instructions in the use of the NDT methods.

2.5.4 Pipelines and risers

Pipelines are non-redundant structural systems, ie a single failure will lead to leakage and subsequent shut-down. For this reason, pipelines receive more inspection attention than fixed or floating structures – and more than pipeline statutory requirements demand.

Unburied pipelines

Unburied pipelines are inspected annually, starting with a baseline survey immediately following pipelaying. The entire length is usually inspected using side-scan sonar, with critical areas being further inspected using ROVs equipped with video cameras and cathodic protection monitoring equipment. One of the operators questioned said that the video/visual survey did not always agree with the results of the side-scan sonar survey; he expressed only 50% confidence in side-scan sonar but 95% in visual inspection. Other operators have used divers to inspect specific items such as retro-fitted cathodic protection anodes.

The primary criterion quoted for selecting areas for visual inspection is the design critical span, which is used to identify significant free spans from the sonar survey. The age of the pipeline and the results of previous inspections also modify the inspection programme.

Subsea actuators have caused problems in the past, and the requirements of inspection, maintenance and repair are now a major consideration in their design. In an attempt to minimise inspection, one operator has eliminated subsea connections as far as possible.

One of the operators questioned has made a considerable investment in the development of a sophisticated 'intelligent' pig for pipeline inspection, and at least one other operator is seriously considering a similar system for routine inspection. The pig would substantially reduce the need for underwater intervention and result in lower overall inspection costs.

Buried pipelines

Side-scan sonar can provide information about the state of the sea bed adjacent to a buried pipeline, in particular the condition of the trench and whether the pipline has been exposed. Sub-bottom profiling gives the depth of cover to the pipeline at intervals corresponding to the crossing points (usually less than 250 m). An operator who regularly uses sub-bottom profiling stated that the entire pipeline length was profiled annually, with side-scan sonar used once every two years.

Comparison of results from the acoustic survey with those from previous inspections provides the basis for more detailed visual inspection. For example, a change in depth of cover may indicate that scour is occurring, whilst a significant local change in trench profile could be indicative of anchor damage.

Direct measurement of cathodic protection potential is not possible with buried pipelines since this requires probe contact, but current density can be measured local to the buried pipeline.

Risers

Risers are normally considered by designers to be secondary components (ie not essential for the structural integrity of a complete installation) but they form part of a highly non-redundant operating system, the failure of which is potentially very costly. Risers and their supports are therefore considered to be primary items for inspection purposes, and all of the operators questioned include them in annual general visual surveys.

One operator believes that many of the problems encountered with risers are a direct result of lack of detail consideration at the design stage. For example, fatigue failures have resulted from vortex shedding, and static overload from underestimation of thermal movements.

2.5.5 Attitude of the certifying authorities

Three certifying authorities were questioned in the survey and others made comments directly relevant to the certifying role. Some of their points concerning fixed installations were:

- It was confirmed that operators tend to perform more inspection than the minimum required for recertification.
- Inspection is sometimes concentrated on detailed NDT of small areas containing known defects at the expense of a broad visual survey by diver or ROV.
- The standard of documentation produced by operators is good.
- In general, NDT practices are satisfactory.
- Two of the three certifying authorities will consider a reduction in inspection requirements for fixed platforms which are designed for redundancy. One of them thought that inspection by ROV to detect member severance might then be adequate.
- Existing methods of continuous structural monitoring are useful when in capable hands, but practical proof would be required of its performance in the specific application before permitting a relaxation of inspection requirements. The results from structural monitoring will be more beneficial if the technique is considered at the design stage. One certifying authority thought it unlikely that structural monitoring could be relied upon as the sole means of inspection.
- Inspection requirements can possibly be reduced (but not eliminated) if more stringent fatigue-life criteria are applied in design.
- Generally, certifying authorities think that inspection should become a more important part of design philosophy, and that operators should be encouraged to feed back performance data from their structures to designers so that subsequent designs can be improved.

2.6 PROBLEMS AND LIMITATIONS OF CURRENT PRACTICE

Different inspection problems face each kind of installation, but generally, an installation will fall into one of two categories: redundant or non-redundant. In this context, redundant means that, in the event of component failure, a system is capable of redistributing the applied loads without immediate risk of failure of the system. An example of a redundant system is a steel jacket platform structure; there are some components in the structure which can fail without immediate risk of complete collapse. An oil-riser is usually a non-redundant system; rupture has immediate consequence.

Designers usually aim to introduce redundancy into important and vulnerable systems. This reduces risk of immediate system failure in the event of failure of one or more components, but makes determination of the load path at any given instant more difficult to predict. In all but the simplest cases, the inspection engineer has to rely on analytical structural modelling to help him select the important areas to inspect. The following discussion centres on the inspection problems which occur with steel jacket structures – the most complex inspection problem currently experienced offshore – although parallel limitations can be implied for other types of installations.

It has been shown earlier (Section 2.3) that the damage that can occur to offshore installations is of two types: progressive damage (such as fatigue and corrosion) and instantaneous damage from vessel impact, dropped objects or damage suffered during transportation or installation.

In the case of progressive damage, predictions can be made of the likely rates of deterioration from theoretical modelling and field experience. Consequently, operators have worked on the basis that they have reasonable confidence that they can discover damage before it has serious implications to the integrity of their installation. Unfortunately, there are two assumptions inherent in this approach which could be unconservative:

- The predictions of where and when fatigue damage is likely to occur are usually made using the results of ananlysis of the designer's computer model of the structure. The degree of detail incorporated in the model is selected from the designer's experience, to highlight possible low fatigue lives in critical areas. However, North Sea experience has demonstrated that, in some cases, areas inadequately modelled have been the sites of fatigue damage with significant consequences. An example of this is the extent of fatigue cracking at conductor guide framing. Another difficulty is that predictions of stress distribution around complex joints are based on extrapolation from simpler joint geometries, and recent test work has shown that hot-spot stresses may be underestimated.

- It is tacitly assumed that, if damage exists in a component, it will be discovered during inspection. Work undertaken by the London Marine Technology Centre and others has demonstrated that the probability of detection (POD) of a defect during a routine inspection is likely to be considerably lower than has been assumed by the industry to date.

A probabilistic evaluation of the current inspection philosophy used for fixed steel structures[2.4] has revealed the inadequacy of examining a small proportion of joints. For a typical ten-year-old structure, inspecting 10% of the joints selected on the basis of lowest fatigue life gives only a 50% probability that we will be inspecting a joint containing an existing crack (see Figure 2.1) – even assuming 100% probability of detecting an actual defect during any one inspection. A joint is defined here as a brace-to-chord weld. The reliability of such structures is more dependent on their structural redundancy than on the effectiveness of the inspection programme.

Instantaneous damage is treated somewhat differently. In instances of major impact, it is extremely unlikely that the incident will pass unnoticed if there are personnel based on the structure. The most obvious damage is likely to be at the point of impact, where plastic deformation usually occurs, and the loadpath from this point into the structure can be assessed with reasonable confidence and the weak points inspected as appropriate. Dropped objects present a more difficult problem; the location of objects on the sea bed gives only a broad indication of their trajectory through the structure, as deflections could be considerable after impact. The impact damage is usually manifested by plastic deformation at the impact site and this is usually identifiable by visual inspection. Disturbance of marine growth often helps to identify the impact location. To complete this exercise systematically can be very time consuming, and will possibly be at the expense of inspection at other sites which could be more critical. The third source of accidental damage is transportation and installation. Damage from this source is very common and its identification usually dominates the first year or years of the in-service inspection.

Some of the problems facing the operator are inherited from poor design. These include inaccessibility to components of key importance to the integrity of the installation and geometrical constraints preventing correct application of inspection techniques. As industry experience increases, so later generations of installations are designed to obviate known difficulties. Reference 2.5 addressed these problems, and an update is contained in Chapter 10 of this document.

2.7 THE NEED FOR A MORE RATIONAL APPROACH

Our understanding of the behaviour of installations in the marine environment, and the associated difficulties of obtaining inspection information, has been augmented by more than 10 years of operating experience in the North Sea since a systematic update of inspection practice was last attempted. Some of the experience represents an extension of earlier world knowledge, but some of the experiences gained in the North Sea are, so far, unique. It is reasonable to assume that the lessons learned in a very short period in the North Sea are a consequence of the harsh environment and that, as time progresses, some of the same difficulties could arise in other waters as the average age of offshore installations increases.

Currently, many operators of offshore installations bias their inspection towards the components which, from structural analyses or historical information, are most likely to show premature damage. At present, then, an inspection plan is geared to respond to items susceptible to damage, and a typical decision tree is given in Figure 2.2.

Although the likelihood of damage is the controlling factor for non-redundant systems, there is another important question to be addressed in the case of redundant systems: "what is the CONSEQUENCE to the system if component 'j' fails"?.

This is of fundamental importance if inspection is to be optimised. Obviously, there is no point in inspecting a component (even if it is very likely to experience damage) if its failure has no impact on the overall system. The difficulty arises when it is not immediately obvious what the consequences of failure of component 'j' will be.

Historically, the conservative attitude of "if in doubt, inspect" has predominated and operators have found it practicable to inspect with adequate frequency all components which they think are likely to show damage. It may be, however, that the number of components which needs to be inspected increases as years go by; either damage is detected which needs careful subsequent monitoring, or later analyses demonstrate that effort is needed in new areas. The operator is then forced to rationalise his inspection, probably by reducing the frequency of inspection of components which have survived without damage for longer than expected.

Although this practice has worked without major disaster for many years, recent experimental evidence (see Section 2.6) has demonstrated that expectation of defect identification during inspection is far higher than the real probability of detection. This is a very important non-conservative discovery, which cannot he ignored as the world's offshore installations get older. The implication is that still more inspection effort must be concentrated on the critical areas. The effect of this on inspection timescale is likely to be just as important as the impact on inspection cost.

Happily, concurrent with the development of industry experience, there have been considerable technical advances in the last ten years. These include:

- the development of new and better inspection techniques
- the development of new theoretical techniques for the interpretation of the significance of damage
- dramatic advances in the field of information technology, which can readily be incorporated into a more effective, integrated method of managing inspection.

The technological advances can be used to good advantage to compensate for some of the difficulties which are stressed above. Consequently, it is appropriate that an integrated rationale be developed for inspection planning of existing as well as future installations to minimise the inspection burden, without increasing the risks to installation integrity. Various approaches are discussed in Section 2.8, and Chapter 3 concentrates on the development of an integrated approach to inspection which it is considered represents a workable compromise between the ideal and the practical.

Some of the lessons learned can now be – and indeed have been – incorporated into better design, both through better detailing and by paying closer attention to the design of key components which will be difficult to inspect when the structure is in service. This is the subject area of Part C of this document.

2.8 ALTERNATIVE APPROACHES

2.8.1 Aims

It was stated in Section 2.1 that the objective of underwater inspection is to ensure a level of confidence in the condition of each component of an installation commensurate with the consequences of failure of that component. The aim of an inspection plan should be to satisfy this objective.

2.8.2 Practical considerations

In practice, the objective cannot be met fully, for the following reasons:

- The detailed theoretical consideration of the significance of every component would require a massive volume of work. Some rationalisation would be required in any practical plan.
- The principal parameters associated with a component's likelihood of failure are loading and resistance characteristics (dependent on material properties, geometry and fabrication quality). The values of loading and resistance cannot be determined with 100% reliability, so there is always a finite possibility that a component may fail despite theoretical predictions (see Section 2.8.3 below and Figure 3.4 in Chapter 3).

2.8.3 Probabilistic versus deterministic approaches

Most current design practice in the offshore industry uses the working stress approach. This means that, for design purposes, safe working stresses are set for each material under various service conditions based on experimental work and practical experience. These safe working stresses are deterministic values; finite quantities are assigned to represent the strength properties of given materials under specific conditions.

In fact, the safe working stresses are conservatively chosen, usually at a level where a predetermined high proportion of experimental tests will demonstrate a strength in excess of the safe working stress. Typically, the probability that the actual strength will exceed the chosen working stress will be 95% or greater; ie, in 100 experiments on the selected material under similar loading mode, 95 will show strength in excess of the safe working stress.

The very fact that there can be variations in a straightforward physical parameter like material strength underlines the uncertainty which must exist about a particular component's behaviour in a working application. The same uncertainties also exist with respect to other inputs necessary to the determination of in-service behaviour, such as fabrication quality, behaviour of specific joint geometries, fabrication quality and the stress environment experienced by the component when in service.

Although each parameter can be examined by experiment and safe (deterministic) values assigned, the resulting design may suffer from:

- undue conservatism
- the possibility of failure due to one or more input parameters falling below the selected design value.

A considerable amount of work has been undertaken by mathematicians and engineers to develop probability theory into working tools. Techniques are now in use which allow designers to take into account the spread of values which could occur for each input parameter, and hence assess the likely overall conservatism of a given design.

Interestingly, although probabilistic approaches have been used extensively in other branches of engineering (particularly the aero-space industry), the offshore design industry has been slow to adopt them. The only codes of practice which currently mention the probabilistic approach for offshore use are Scandinavian.

The case for the introduction of probabilistic techniques to offshore inspection is very strong. This is because there are some inputs to the strategy about which our level of confidence will be low and an understanding of the likely spread of inspection results will help in the determination of a suitable level of inspection. When determining a plan for a given inspection season, the engineer will want to know:

- what is the consequence of failure of the component under consideration?
- what is the likelihood of there being a defect in this component?
- what will it cost to inspect to give an adequate level of confidence that a defect which exists in this component will be discovered?
- is it practicable to inspect this component this season?

The answer to each of these questions is a function of many considerations, almost none of which can be determined with 100% confidence. To attempt a rigourous mathematical determination of the interdependence of all parameters in answering these questions for every component in an installation is a laudable aim but the sheer size of the problem renders the approach impractical. Because there will be uncertainty in the spread of values selected for a given input parameter when making a mathematical appraisal, the approach must in any case be treated cautiously. Nevertheless, the development of a rational approach to inspection cannot afford to ignore the potential of probabilistic techniques, even if some compromises are necessary to make the overall approach manageable in size and comprehensible to the essentially pragmatic end-user.

Whereas deterministic methods provide a simple and easy-to-use approach, the probabilistic approach presents a more realistic picture. The difficulties of using the probabilistic approach centre on determining the probability density functions of uncertain inputs (such as inspection reliability, material strength and loading) but the extra cost and timescale involved might be a worthwhile investment for components where the (conservative) deterministic approach indicates a need for significant levels of inspection or high initial capital outlay. Appendix 4 discusses the probabilistic approach in more detail.

2.8.4 Possible alternative approaches

Fail-safe design

The traditional engineering approach to a system made up of components that are damage susceptible is to design the system to be safe should any reasonable amount of damage be sustained. This philosophy was rationalised by the aircraft industry in the 1950s into the 'fail-safe' approach. Implied in the approach is a minimum defect that is detectable during routine inspections and that will be tolerated by the system between inspections. The procedure involved in the approach for offshore installations and pipelines is illustrated in the form of a flow diagram in Figure 2.3.

The philosophy requires the definition of an acceptable level of damage, which reflects the reliability of the whole structure. A number of possible alternatives are presented in Figure 2.3; in practice a combination might be used. In the case of fixed steel platforms, for example, whilst the structure might be designed with sufficient redundancy to tolerate the loss of a brace between inspections, the resultant increase in fatigue damage must also be limited. Obviously, the damage criteria would have to be set very carefully!

Consideration must also be given to the reliability and resolution of inspection techniques which are chosen to support the philosophy, and to the loading criteria adopted for theoretical studies.

To investigate every component in a proposed design represents a considerable analytical effort but the approach lends itself to cost optimisation, by using modelling simplifications and concentrating on areas critical to the integrity of the system.

The optimum approach may be achieved by selecting different damage criteria for different parts of the structure. For example, it *may* be more cost-effective to design structural elements in deep water for inspection by ROV, with those near the surface being designed for diver intervention. This is the basis for the 'minimal inspection' approach described below.

The fail-safe approach is considered again in Section 9.2.

Design for minimal inspection

If acceptable damage criteria can be set for all components of an installation, then it might be possible to design them in such a way that inspection should never be needed during the service lifetime of the installation. This may in practice lead to extremely conservative design and very high capital cost. The trade-off between high capital expenditure and likely lifetime inspection cost would have to be eveluated and design decisions taken accordingly.

This approach is discussed more fully in Part C, but it should be noted that, because it is not possible to be 100% confident of any theoretical assessment (for the statistical reasons outlined above), it would be unwise to decide not to inspect at all, regardless of the degree of designed redundancy.

Ranking tree

The basis of a 'ranking-tree' approach is that the components of the installation are sub-divided into broad categories (risers, structural members, joints, pile guides, etc) and ranked in order of inspection importance. This is achieved by allocating a score to each component for each characteristic of that component which has an impact on its importance for inspection. For example, the component's failure might have a dramatic impact on the integrity of the installation as a whole, so it would have a high score under 'component criticality'. The same component might, however, be very unlikely to fail, and so it would have a low score for 'likelihood of failure'. These part scores, together with scores for other criteria of importance, would be combined to give an overall ranking of that component's overall importance as an inspection priority.

Whereas the two approaches described above must be selected before final design of an installation, the ranking tree approach can be used either for new installations or for assisting in preparation of inspection plans for existing structures. The ranking tree approach developed in this document is intended to provide the engineer with a working tool with which he can identify components or areas of an installation that appear to be worthy of more detailed investigation. It is the basis for the philiosophy developed in Chapter 3 and the practical approach described in Parts B and C of this document.

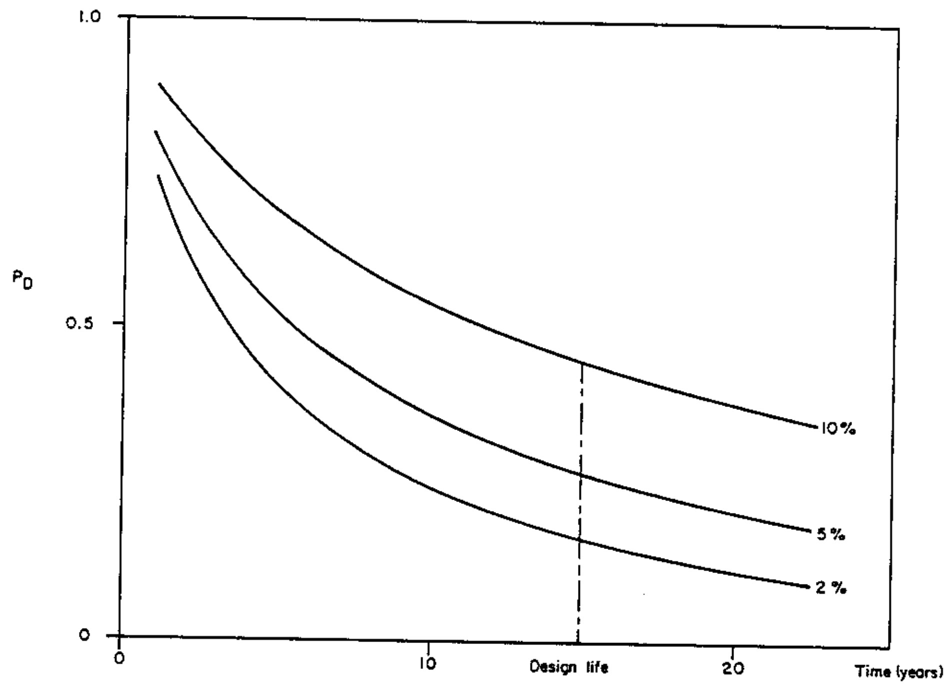


Figure 2.1: *Variation with time of the probability of crack detection with percentage of joints inspected as a parameter (assumes 100% reliability of inspection technique)*

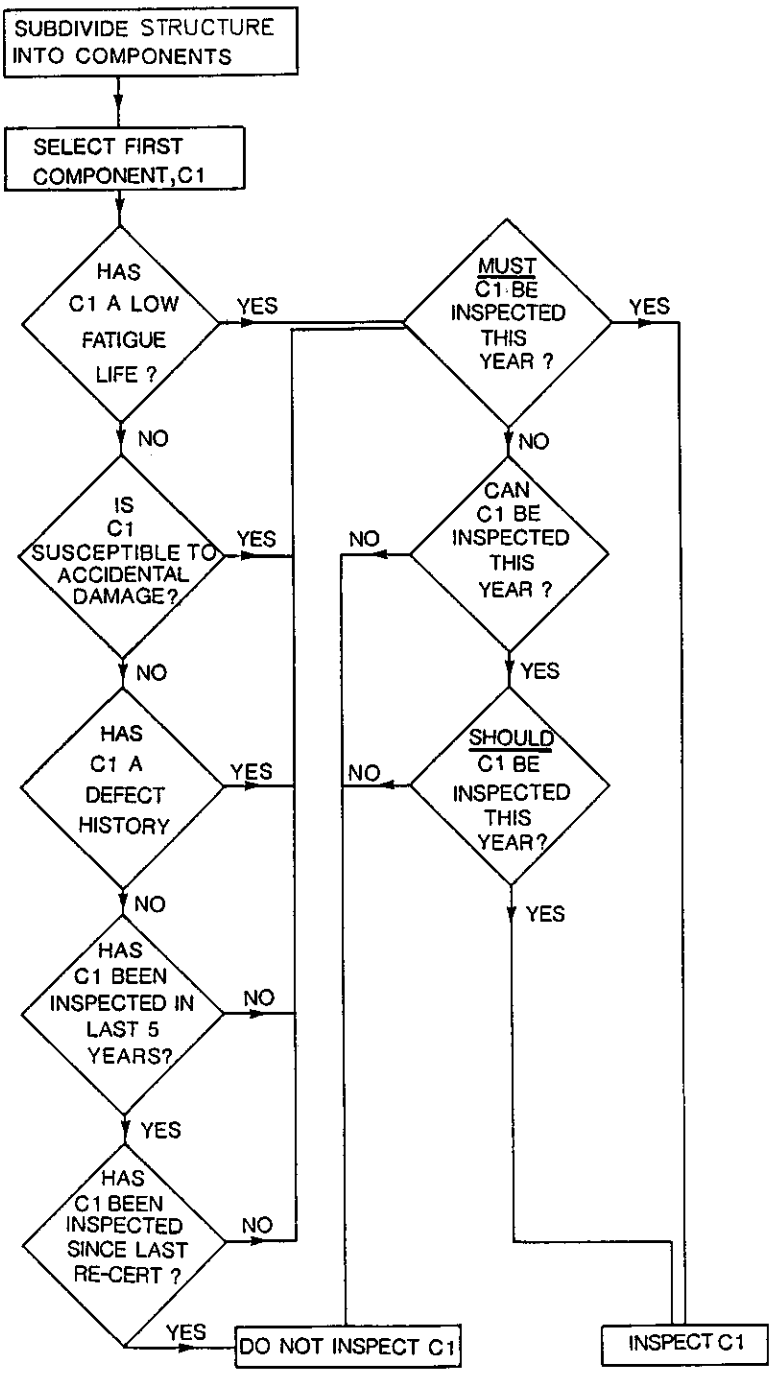


Figure 2.2: *Simplified decision tree illustrating typical current practice in inspection planning in year N*

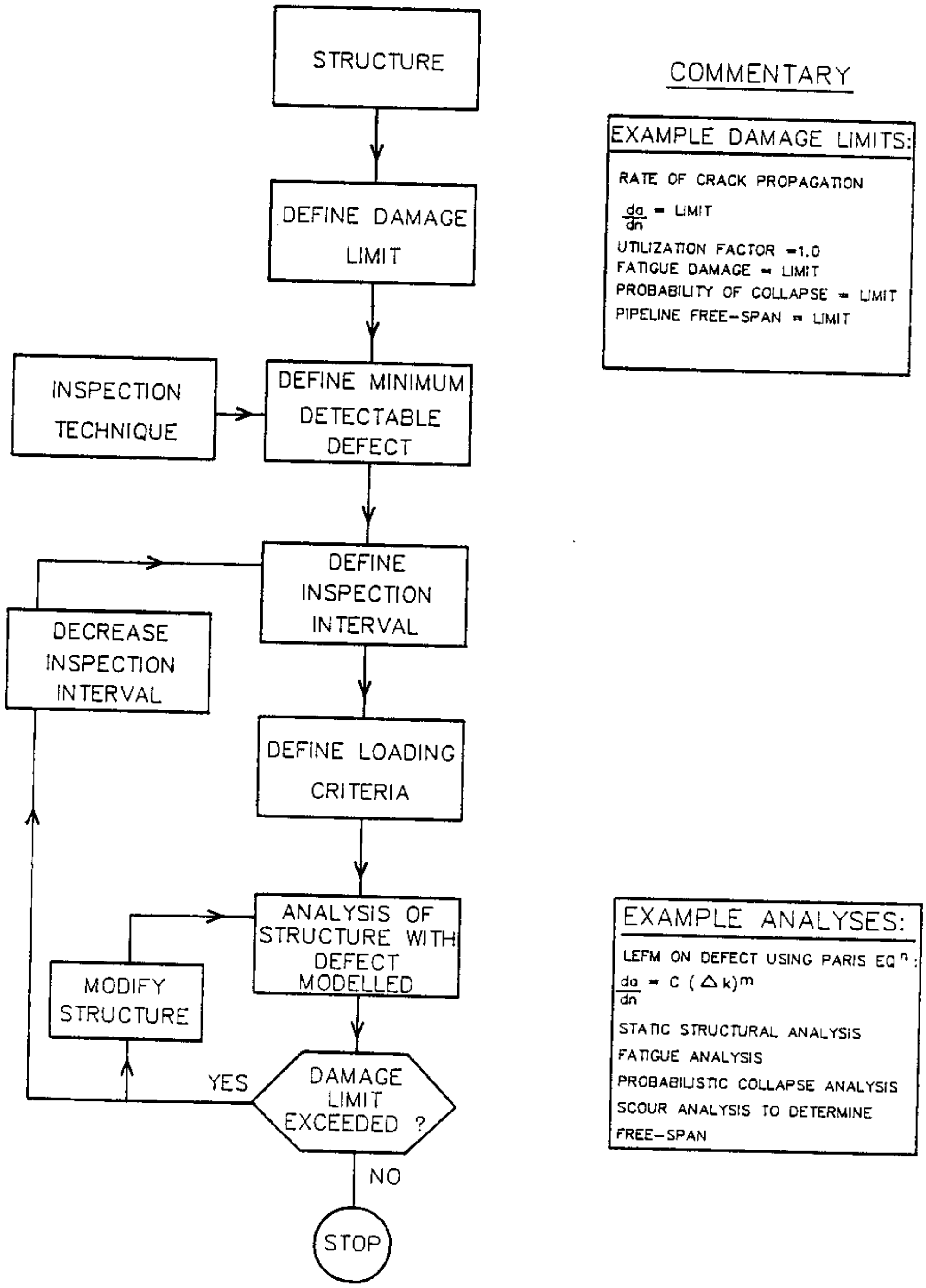


Figure 2.3: *Typical flow diagram for 'fail-safe' design*

3 Basis of a rational approach

3.1 OBJECTIVES

The fundamental objective of inspection is to meet the criterion set out in Section 2.1.1, which is:

> ". . . . to provide a level of confidence in the condition of each component (of an installation) commensurate with the consequences of its failure."

In addition, the following objectives need be taken into consideration in developing a rational philosophy:

- Any philosophy should take into account advances in technology which could be used to advantage. These include computing, inspection techniques and damage assessment techniques.
- The philosophy should be as independent as possible of inputs to which high degrees of uncertainty can be attached. At the time of writing, the low probability of detection of defects is of particular concern.
- The method should be able to accommodate either refinement (including implementation of relevant future technology developments) or simplification, according to the needs and resources of the user.

Furthermore, if a new inspection strategy is to be implemented, it must satisfy the following citeria:

- there should be no reduction in the level of confidence in the integrity of the structure
- either cost or risk should be reduced, compared with the existing inspection strategy.

Little purpose is served in implementing an inspection plan which does not meet these objectives.

3.2 PRINCIPLES OF THE PROPOSED RATIONAL APPROACH

3.2.1 Rationale

Chapter 2 describes some of the problems with existing underwater inspection practice and identifies the need for a new, more rational, approach. This chapter develops a possible approach which could be adopted in part or in full to ensure that inspection effort is directed as effectively as possible.

Currently, as was described in Section 2.6, inspection is weighted towards items perceived to be susceptible to damage. Recent experimental evidence has shown that expectation of discovering a defect during inspection is unrealistically high and the implication is that more inspection effort will have to be expended at each critical site.

To maintain the inspection burden at a manageable level, some form of rationalisation is necessary. If the amount of inspection at each site is likely to increase, then this is best approached by reviewing the possibility of inspecting fewer components. At the same time, it is desirable that no loss of confidence in the servicability of the system results from this reduction.

It is proposed that two techniques be introduced into the preparation of inspection programmes to ensure that the rationalisation is optimised.

The first expedient applies to all redundant systems. It is recommended that the question "what is the consequence of failure of component 'j' on the integrity of the system" be asked before the question "what is the likelihood of failure of component 'j'". An inspection programme based on this logic would require classification of the components of a system according to the following criteria:

- consequence of damage in a specific component to the integrity of the installation
- likelihood of failure of the component.

The second expedient that can be used to reduce the number of components inspected is to carry out more detailed analytical studies on components perceived to be damage susceptible, to gain knowledge of the likely behaviour of a defect. Currently, when a survey identifies damage, assessment of the damage is carried out and a decision taken on remedial action. In fact, many components may be highly tolerant of defects. Using modern assessment techniques (reviewed in Chapter 8), understanding of the behaviour of defects, particularly crack-like defects, has improved. If it can be shown that:

- a crack of a given size is certain to develop very slowly under fatigue loading
- the defect will not cause catastrophic (brittle) or static failure of the component under maximum loading,

then it may be possible to increase the period between inspections. This approach can be applied to any subsea component susceptible to fatigue damage, and parallel rationales could be applied to other types of damage.

In the past, the offshore industry has used damage assessment techniques solely for interpreting the implications of existing damage. The proposed rationale adopts a powerful extension of the same techniques, in which the likely behaviour of damage in a failure-critical component is investigated by postulating possible defects in analytical models of the component and investigating their likely course and timescale to failure *before the component is ever inspected.*

A component which is demonstrably both critical to the integrity of the complete system of which it is a part, and is likely to experience damage, is termed 'fracture critical'. Figures 3.1 and 3.2 show decision trees for inspection planning using this approach.

An optimised inspection programme would make use of the above techniques together with the current criteria for inspection. The hierarchy of questions to be addressed in this approach is:

1. What are the effects of damage in component 'j' on the whole installation?
2. Is component 'j', which is known to be defect critical, likely to show premature failure (from analysis results, previous history, susceptibility to impact or corrosion damage)?
3. How stable is a small defect at site 'j'?
4. What is the cost of ensuring that defects at site 'j' are identified in the field before they reach critical size?

The aim of this approach is to bring the significant technological advances of recent years (together with the collected experiences of the industry) to bear in such a way that inspection costs are minimised without penalising confidence in system reliability. The implication of this approach is that some of the field inspection cost will be replaced by increased desk-study work. It is worth noting that, at current relative prices, a single day saved from the offshore inspection programme justifies a man-year of engineering effort.

The engineering tools to support this effort are largely already in existence, so that a change of approach may be considered for existing installations as well as for future offshore developments.

In recognition of the fact that our understanding of the behaviour of a system – particularly a redundant system – cannot be perfect, the developed rationale must include provision for random inspection of the non fracture-critical components of a system.

3.2.2 Discussion

The approach developed in this document aims to address all the topics which have a bearing on underwater inspection, and as a result is rather complex. It is, however, broken down into elements so that the user may implement the various aspects progressively, choosing only those elements which he considers will be of benefit.

The system proposed requires a considerable quantity of data to be processed when planning the underwater inspection, and it is recommended that a computer database system would be appropriate for most installations if a simplified version of the total system were to be implemented. This would lend itself naturally to the points systems proposed for inspection priority ranking and is discussed further in Chapter 5 of this document.

It is emphasised that this approach is for inspection planning. Damage discovered during an inspection should *always* be assessed using the best inspection and theoretical interpretation techniques available. After assessment of damage, a decision on whether to repair and what revised inspection strategy should be adopted for future inspection of the component is fed back into the inspection planning database described in following sub-sections.

3.2.3 The review panel

One of the paramount requirements of a rational inspection planning system is that the users, who will change as years go by, use a consistent approach. Also, the proposed method requires the establishment and maintenance of a database of inspection information, some of which (as will be demonstrated later) must be based on subjective judgements.

To help in making these judgements, to assist in inspection planning and to lend a continuity and consistency of approach, a 'review panel' is proposed. The review panel would contain a selection of experts in all of the following areas:

- structural design
- quality assurance
- inspection
- diving and underwater vehicle operation.

It is also probable that there would be specialist metallurgical and corrosion input and possibly input from the certifying authority.

The functions of the review panel would be:

1. to provide, from calculation and experience, input into a logical plan for assessing the importance of each component
2. to make judgements on which items, from a list of preferred items, shall be inspected
3. to advise on inspection methods
4. to liaise with the certifying authority.

There would be some benefit if the same group advised the individual responsible for the offshore inspection management, in which case suitable quality and reliability audit by independent specialists may be required.

It is suggested that members of the panel serve for a minimum period with overlaps to ensure continuity and consistency.

There is a further duty of the review panel for new installations and for in-service installations about to adopt the proposed new method, which is:

5. to prepare written guidance on the operation of the overall inspection system and to define firm rules for any processes used in making subjective judgements.

3.2.4 Summary

The principles to be adopted for the modified approach are summarised as follows:

- Decisions on which components to inspect should be based on the following hierarchy:
  - consequences of component failure
  - likelihood of component failure
  - cost and reliability of inspection.
- For fracture-critical components, theoretical damage assessment techniques should be used *before* inspection takes place, to gain an understanding of likely modes of defect progression and times to failure.
- When damage is detected during an inspection, the component should be treated as a special case until it is satisfactorily dealt with; it is necessary to assess the defect, consider remedial action and consider requirements for future inspection and monitoring.
- Consistency of approach will be ensured by having an expert review panel and written rules for the operation of the inspection system.
- In making decisions, objectivity must be maximised. The best possible information should be gathered before taking subjective decisions.

3.3 DEVELOPMENT OF THE METHOD

3.3.1 Overall approach

This section outlines the manner in which the principles described above are fulfilled. The methodology is represented as a flow diagram in Figure 3.3. The full method can be applied to any offshore installation, although its effectiveness will be most apparent on redundant structures. Details of its practical application to existing and new installations are to be found in Chapter 5 and 9 respectively.

The backbone of the proposed methodology is an inspection priority ranking system. The ranking for each component is derived from the logic:

- what is the consequence of failure?
- what is the likelihood of failure?

Each question is sub-divided in such a way that relative values can be assigned numerically and a compound ranking is derived to give an idea of the component's overall 'criticality rating'.

The components with high ratings are reviewed to identify inspection methods appropriate to their likely failure modes, and the likely cost of executing inspection to a suitable level of confidence is determined.

From the criticality of the component and the cost of each inspection of that component, a picture of its impact on the lifetime inspection costs of the complete installation can be built up. For the purposes of this document, the quantitive representation of this parameter is called the 'compound weighting'.

If the likely lifetime inspection cost is high (high compound weighting), detailed studies are carried out on the component. Up to this point, many of the factors contributing to the compound weighting will have been derived subjectively. Theoretical techniques are now brought to bear to give a more objective understanding of the component's likely behaviour in the field.

After studies have been completed, it may be appropriate to re-rank the component, adopt special measures for its future inspection, or decide that strengthening now (before damage is discovered) will be cost effective in the long term.

The overall ranking of components, modified as appropriate following the theoretical studies, gives a picture of the inspection priorities and the ranking can be used by the review panel to identify preferred components for attention in the next inspection season.

After inspection, the results of component condition (such as corrosion condition and quantity of marine growth) are fed back into the database and the component is re-ranked as appropriate. The exception is the case of damage being discovered during inspection in which case the component is treated as a special case; further site inspection work might be executed to characterise the defect and then detailed studies carried out to determine the correct remedial action.

3.3.2 Practical considerations

Size of analytical problem

Ideally, each component should be considered individually, and decisions taken about its importance in the overall system to be inspected should be made following objective studies. The studies would need to consider both the likelihood of component failure *and* the impact that failure would have on the integrity of the whole system. The former requires a detailed knowledge of the loading regime and component resistance and may necessitate finite-element or fracture-mechanics analysis. The latter implies redundancy studies; for example, examining the effect of removal of the component from the analytical model of the complete system and investigating the effects on the remaining system. These effects could include changed fatigue lives in addition to the effect on safety factor against static collapse.

It is immediately apparent that an almost infinite set of damage scenarios, including combinations of different sorts of damage, could be postulated.

Inspection reliability

It has been pointed out above that expectation of defect discovery during inspection probably exceeds actual probability of detection (POD). This has important implications.

Firstly, it implies that additional inspection is required at each site actually to achieve the level of reliability that the industry currently assumes (see Section 3.2.1 above).

Secondly, it highlights that inspection planners should take careful note of the capability of proposed techniques within the relevant environment, which is likely to be much worse at 50 m depth in cold water than the same technique would be in air. If possible, the inspection planners should ask, for a given component, technique and inspection environment, "what is the minimum defect size that is *certain* to be detected?" and "what is reasonably likely to be detected?" rather than, "what is the minimum defect size that *can* be detected by this technique?" It must also be noted that the effectiveness of the technique is often also a function of its operator. Every effort should be made to minimise any requirement for interpretation by underwater operators, whose attention should be addressed solely to correct application of the technique if possible.

In fact, there can never be certainty about defect detection and a practical inspection plan must take this into account when planning levels of inspection.

Statistical uncertainties

Regardless of the objectivity of detailed studies, there are statistical uncertainties associated with all the factors which contribute to an inspection programme. For example, the maximum load in a member may vary from the predicted maximum load and the strength of a member is also subject to variation about a calculated mean strength. Consequently, there is a finite possibility that the actual maximum load may exceed the actual strength of the component, as shown in Figure 3.4. Computation of likely distributions for all variables represents an impractical computing problem. In practice, finite (deterministic) values would have to be assigned to each parameter and an assessment made mathematically of the likely range of real fracture criticality based on sample data (this is known as 'benchmarking').

This problem (allied to the uncertainty associated with probability of detection) can and should be handled practically by carrying out random inspections on non-critical components. This should be easy to accommodate in a real inspection programme; components would be selected on the basis of convenience to vessel location and inspection priorities on fracture-critical components.

Loading regime

The loading regime in each significant component would be generated as a matter of course during the design process but whether or not a component is fracture critical may be a function of the relevant loading combinations. For example, if a member acts in compression for 90% of its life, but comes into tension occasionally during storms from a particular direction, the member cannot be simply classified as a tension or a compression member.

Certification requirements

The requirements of certifying authorities are, strictly, irrelevant to the development of an OPTIMISED inspection strategy. Nevertheless, the certification system is an important part of the quality plan, and development of an optimised strategy in conjunction with the certifying authority would be rational.

Operational considerations

Operational considerations the inspection planners need to address include:

- choice of intervention method (eg saturation, air diving, nitrox, minibell)
- specification and location of the diving support vessel or air diving spread (eg umbilical length, likely interruption from drilling, bunkering, flaring)
- diving requirements and regulations (eg bottom time limits, team size)
- estimated time 'waiting on weather' (depending inter alia on time of year and side of platform)
- cleaning requirements and methods
- cleaning time
- time taken to inspect
- overall spread time.

Guidance on these aspects is given in Chapter 7.

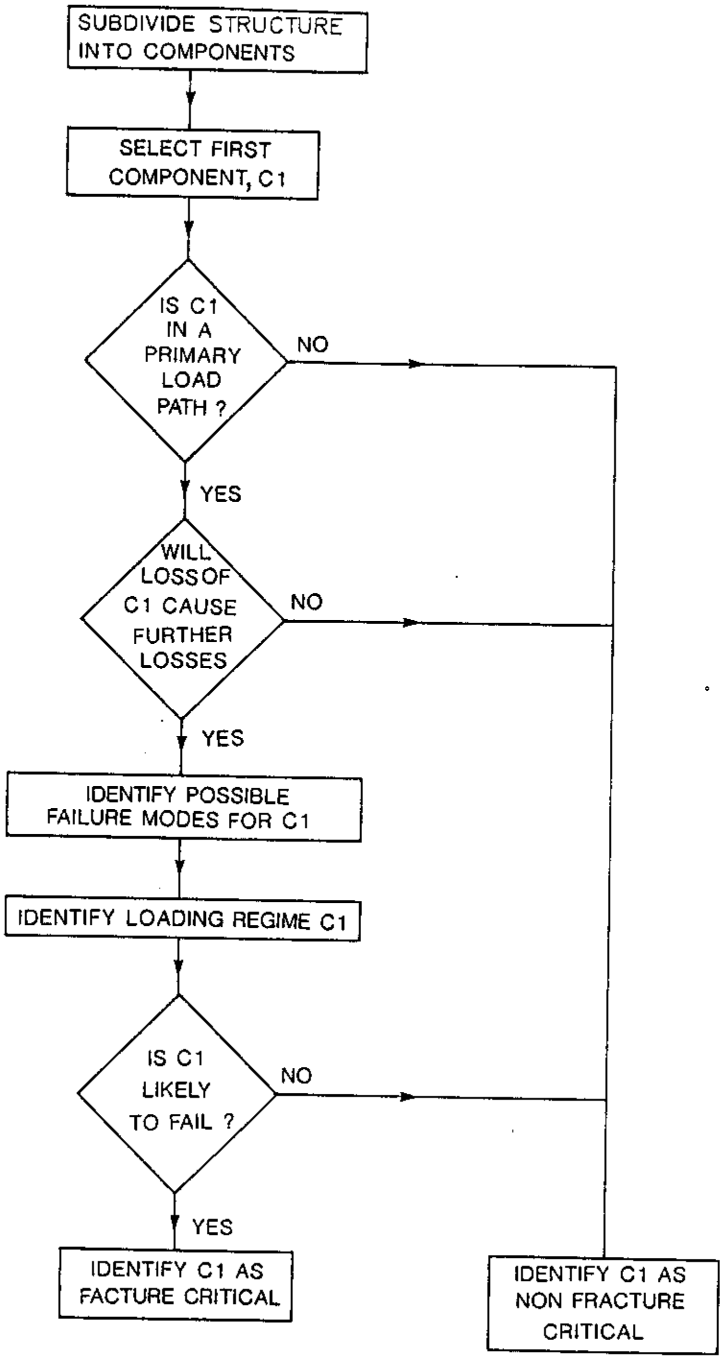


Figure 3.1: *Part of decision tree for development of an optimised inspection strategy*

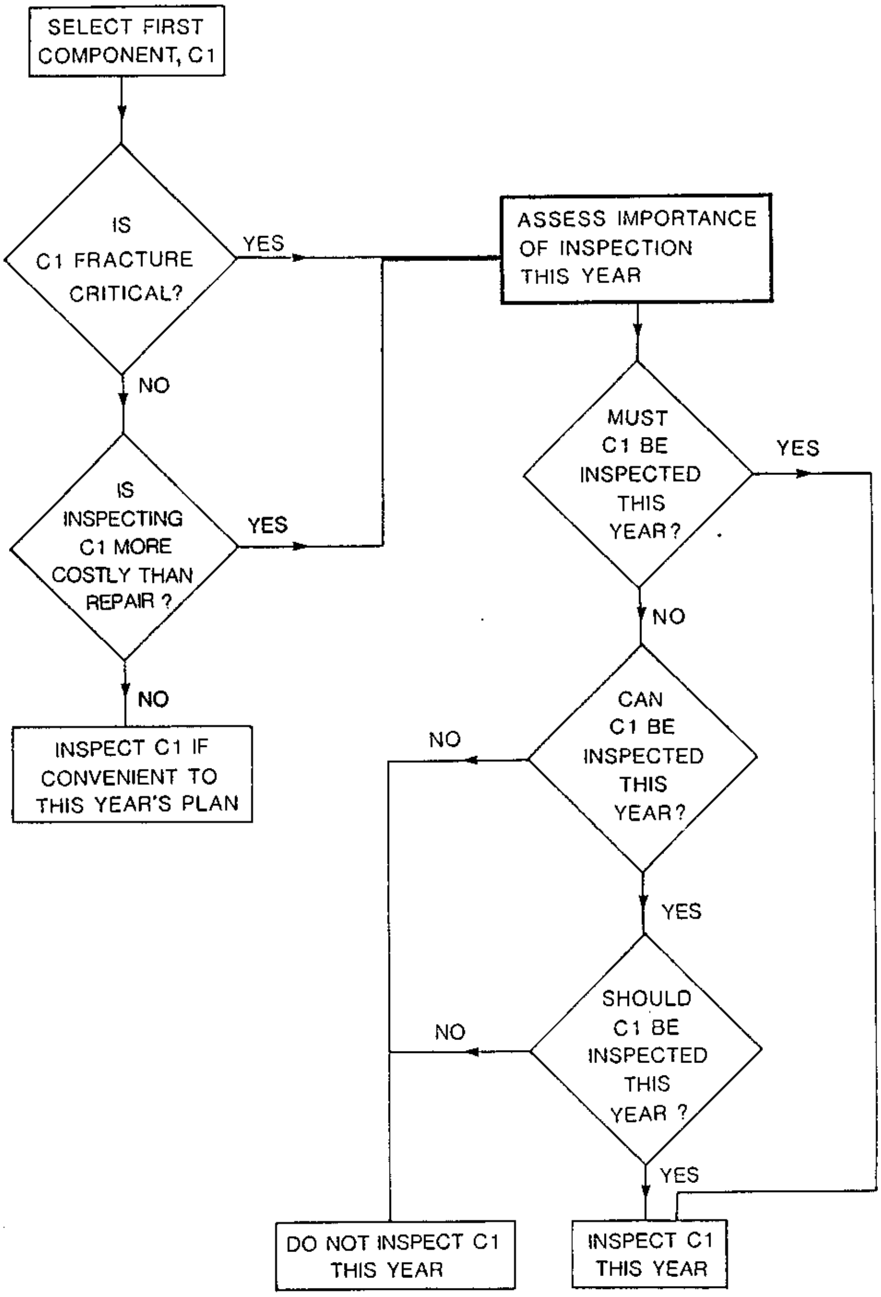


Figure 3.2: *Proposed philosophy (simplified) for inspection planning, year N*

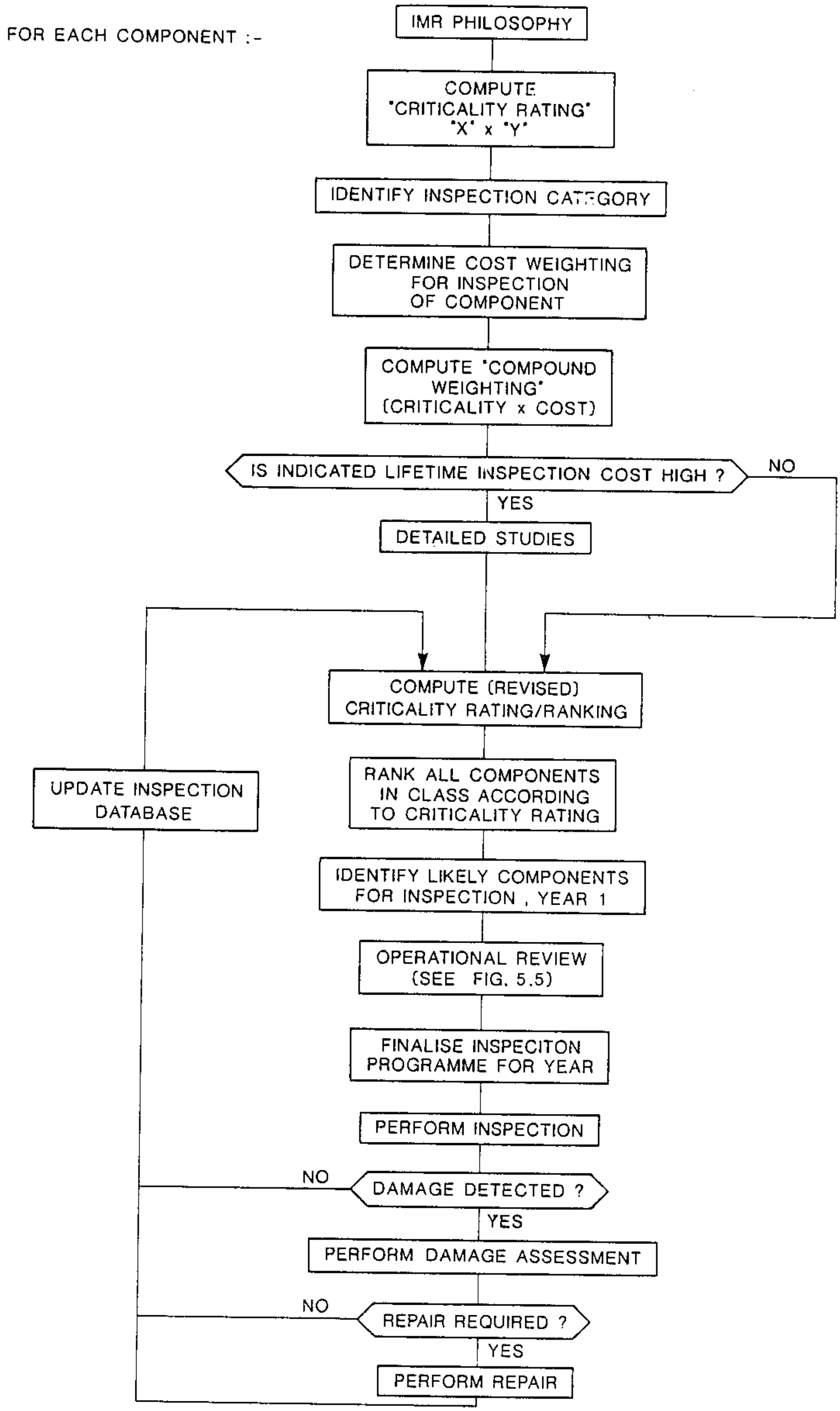


Figure 3.3: *Flow diagram to indicate the formulation of the annual inspection/repair programme*

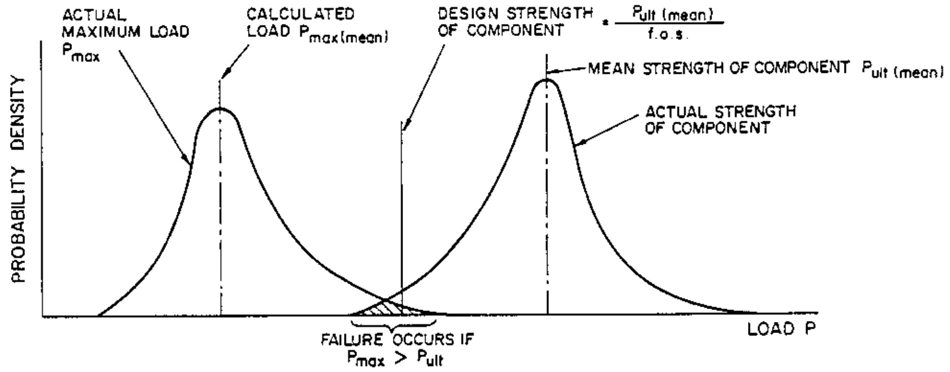


Figure 3.4: *Load and strength distributions showing the probability of load exceeding strength*

Part B

Effective implementation

4 Damage, deterioration and fouling

4.1 INTRODUCTION

All parts or components of any structure may sustain some damage or deterioration before the overall safety or integrity of the structure is threatened, and offshore installations are no different from land-based structures in this respect. The amount of acceptable damage or deterioration varies throughout the structure, from little more than nil in certain critical members to complete removal in redundant members. For a hypothetical and generalised installed jacket structure, Figure 4.1 indicates which members are likely to be in which category. The figure only shows the primary members of the structure, ie the members in the main frame. Secondary members attached to the jacket can also be categorised in a similar way by the amount of damage they can safely sustain.

An overall indication of the causes of damage or deterioration to fixed steel platforms in the North Sea is given in the pie-chart of Figure 4.2. The chart is based largely on data from Reference 4.1 supplemented by data gained during Study 2 (see Section 1.3) and is confined to damage that was severe enough to require repair. The data may not be complete – operators are sometimes reluctant to disclose all information about platform defects – but the figure does show the importance of accidental impact and fatigue as causes of damage.

The results of a study of structural damage to 21 steel platforms installed in the North Sea between 1971 and 1978 are summarised in Table 4.1. The study[4.2] was based on records from underwater inspections up to 1984. Cracks were reported in 12 of the platforms and dents in 15. Of the structural defects, the most common causes were:

- direct design deficiencies, eg incorrect estimation of wave loading, hot-spot stresses or material fatigue properties
- indirect design deficiencies, eg insufficient access for proper fabrication
- construction deficiencies, eg faulty weldments (accepted due to poor quality control), undercuts, alignments outside tolerances
- accidental events, eg collisions and dropped objects resulting in gouges or dents.

An additional type of damage highlighted by Table 4.1 is pitting corrosion. It was reported on virtually all the platforms and, whilst not a major problem, it is a cause for concern.

The principal types of failure resulting from damage include:

- fatigue
- fracture
- member collapse
- joint collapse
- excessive corrosion.

Although these failure types are distinct, they are in many circumstances inter-related. For example, fracture is often the premature termination of a fatigue problem, and member collapse and joint collapse occur together when there has been gross local overloading on a structure. The type of failure is governed by a limited number of parameters, of which the most important are:

- loading type (eg static or cyclic, tension or compression)
- structural geometry (eg slender or stocky, designed for tension or compression)
- structural detailing.

For each potential failure mode it is essential to have an appreciation of the visible evidence of deterioration that precedes it, since the underwater inspection plan (see Section 5.2) must be designed to detect this evidence:

- *For fatigue cracks*, the visible evidence is generally a line indication on the surface, which may either be detected by MPI or by close visual examination, depending on its size. It is somewhat more difficult to detect cracks growing from the inside of a member outwards – either underwater radiography or ultrasonic methods are needed, or a flooded member detector may be used to detect this sort of crack once it has grown to through thickness. If the flooded member detector is to be used, it is essential to verify that joints would have adequate residual life with through-thickness cracks, to ensure that cracks could be detected in this way before final failure occurred.

- *For ultimate load failure*, there is generally little evidence of distress until a local failure has occurred, and this may be detected by general visual inspection or by structural monitoring. Failures of this type are usually caused by exceptional loadings, such as boat impact or from dropped objects; inspections should thus be carried out as soon as an incident is reported, or if evidence such as unexplained debris is encountered on the sea bed.

Known potential failure mechanisms, their locations and their associated damage are summarised in Table 4.2 and described in more detail in the following sections. But the possibility of quite unexpected damage and failure should not be ignored. If all the lessons have been learned from the shortcomings of early platform design that have come to light, the current generation of offshore installations should not suffer from the defects of the earlier installations, eg cracking in conductor guide frames, caisson support defects, etc. However, what might be called second-generation defects are only now becoming apparent on the early structures. Examples of these are ineffective corrosion protection and problems with single-sided butt welds. Defects in this category are likely to be discovered with increasing frequency; there is no reason to believe that they have been designed out of the later generations of structures.

4.2 TYPES OF DAMAGE AND DETERIORATION

4.2.1 Design details

Rigidly attached appurtenances

A number of early offshore structures suffered from poorly detailed supports for appurtenances. A common failing was that rigid welded supports were used which attracted framing loads from the primary structure. The resulting stresses sometimes led to failures in the appurtenance supports (and even to loss of the appurtenance) and also to fatigue cracking in the main members involved.

Flooded members

Problems have been encountered on structures where insufficient attention has been paid to the flooding of hollow members. This includes instances where members have been designed incorrectly so that overstress occurs under normal hydrostatic loading, and also cases where the actual condition of flooding has differed from the designer's original intentions, possibly as a result of poor detailing of the flooding holes. In one instance, diaphragm stiffeners in an X-joint were found to be severely overstressed because of poor detailing which caused the space between the stiffeners to remain unflooded. The stiffeners were having to carry the full hydrostatic loading on one side only. By their nature, member flooding problems of this type (ie not associated with fatigue cracking) are confined to the lower levels of structures installed in medium to deep water. The actual state of member flooding may be readily detected by use of appropriate inspection techniques (see Section 7.2.6).

4.2.2 Fabrication defects

It is recognised that welding of a quality unacceptable by current standards succeeded in entering service in some early installations. A combination of poor design, poor quality control and poor welding procedures led to fabrication defects. These defects are generally confined to single-sided welds.

In these installations, subsequent fatigue damage may be a direct consequence of the poor fabrication. Fatigue damage initiates at microscopic defects in welds, and poor fabrication techniques increase the likelihood of such defects occurring. The assumptions made in design are based on specific standards of material and fabrication and, should unexpected defects be present from fabrication, environmental loading can lead to premature fatigue crack propagation and subsequent failure. The location of fabrication defects is difficult to predict, but experience has shown that potential problem areas exist in:

- weld repairs
- closure welds
- departures from design specification
- welds with poor access
- sites where erection aids have only been partially removed.

4.2.3 Transportation and installation damage

Occasionally, damage has been sustained by a platform during its journey from fabrication yard to site. Damage has been caused by excessive motion in terms of either amplitude or duration, because the design sea state was exceeded or because transportation took longer than envisaged. Under these circumstances, both static overload and fatigue damage can occur.

Most of the incidents of installation damage have been caused by dropped objects and result in dents and gouges. Misalignment of piles and conductors during driving has also resulted in considerable structural damage. Structural failure due to wave slam and interference from launch barge attachments have also been experienced.

4.2.4 Damage from operational activity

Ship impact

Impact damage, eg from manoeuvring supply boats, may range from minor denting to complete severance of structural members as a result of combinations of shear, bending and tensile forces. Even if the impact only results in a dent and not rupture, the dent may significantly reduce the residual strength of the member. Impact is usually noticed at the time of the collision, although minor damage may pass undetected and unrecorded. On one occasion some years ago, a ship fractured four major members of a platform near the sea surface. The effects of this accident were compounded as the members caused further damage as they fell to the sea bed. Structural members in the splash zone are particularly susceptible to ship impact.

Accidental collisions are very common, and most platforms can be expected to sustain some damage, albiet slight, each year. However, alterations made to operational procedures have now reduced the number of ship-installation impacts, and northern North Sea installations tend to be less vulnerable to ship impact damage because of their cantilevered decks and the greater reach of platform cranes. Code requirements for ship impact in the North Sea have recently been revised and may result in fewer occurrences of damage as effective fendering systems are more widely adopted.

Dropped objects

There is always a risk of items of equipment being lost overboard from platform topsides. Incidents are usually reported, but there have been cases of objects not recorded as dropped being discovered during seabed surveys. Even for a reported incident, it may be difficult to confirm and locate any structural impact damage because of the unpredictable trajectory of an object falling through water. Damage is likely to be in the form of dents and gouges. Dents often contain cracks in areas of reduced toughness (due to cold working) and a propagating brittle crack emanating from a dent has been reported.

Drilling cuttings

On a number of structures it has become apparent that insufficient attention was paid during design to the disposal of drilling cuttings. The cuttings then accumulate around the base of the structure, applying additional loads to the members at the sea bed. In some instances the deposits reach the next-to-bottom framing level, typically some 10 m above the sea bed. Detailed studies have shown that the pressures from drilling cuttings can cause substantial overstressing of the members, and indeed one case of member collapse has already been reported.

4.2.5 Corrosion

Different types of corrosion cause damage to offshore installations:

- *General corrosion* is the term applied to corrosion which spreads evenly over a steel surface. Its rate, and therefore the loss of structural strength with time, can readily be calculated. It is important to ensure, through repeated measurements, that the loss of section does not exceed acceptable limits.
- *Pitting corrosion* is localised and deep, but the pits are often obscured by corrosion products. A common location of pitting corrosion is around welds, where its cause is galvanic corrosion.
- *Galvanic corrosion* occurs when two different metals are placed in contact in an electrolyte, the chemically more reactive one being corroded. Appropriate cathodic protection (CP) measures should be taken to prevent galvanic corrosion.

- *Corrosion fatigue* is the simultaneous occurrence of cyclic stress and corrosion. Pitting or other localised corrosion has the most effect on the fatigue life. A corrosion fatigue failure is normally accompanied by a large number of cracks much finer than those where failure actually occurs.

Corrosion is not generally a major problem in offshore installations. Generous corrosion allowances are designed into members in the especially susceptible splash zone and the submerged structure is protected by a CP system. However, problems have occurred when the protection system has proved inadequate or has broken down. Poor CP system design has resulted in under-protection at some locations, usually in the less accessible parts of the structure or where the locations of anodes cause localised 'shadowing' at joints. Poor earthing of secondary attachments and piles has also led to excessive corrosion. Unintentionally rapid consumption of CP anodes has been reported during repair and installation activities – as a result of interference from electrical welding work. Incomplete removal of installation attachments results in local overload of protection systems unless allowance has been made in the CP design for the extra mass of steel. Buoyancy tank supports and pile guides would cause this type of overload. Pitting corrosion can also occur as a result of CP underprotection, especially in the early phases after installation.

Corrosion problems generally appear either as excessive pitting at weldments or as 'knife-line' or crevice attack in the weld cap toe.

Experience has shown that steels with high hardness microstructures are more susceptible to corrosion. Higher rates of corrosion are thus prompted by the following welding conditions:

- low preheat
- low heat input welding
- uncontrolled post-weld cooling
- high carbon equivalent steels.

The comprehensive database of fabrication records and procedures implemented by some operators can be used to identify the locations with a high risk of excessive corrosion of this type. Experience has shown that these conditions often occur in caissons and similar appurtenances, and corrosion failures have resulted.

It is a reasonable approximation that corrosion rates in sea water double for each 10°C rise in temperature. Production risers often carry oil or gas at elevated temperatures and are typically at 60 to 70°C on the outside surface. At these temperatures, an unprotected riser could corrode by about 4 mm per year.

Intentionally flooded hollow members also have special corrosion problems. It is desirable to seal the flooding holes after platform installation to exclude oxygen and thus prevent corrosion, but the entrained water should be dosed to kill any sulphate-reducing bacteria which would otherwise flourish in the anaerobic conditions.

4.2.6 Fatigue damage

Fatigue cracks, and ultimately fatigue failure, result from the application of a cyclic stress (such as occurs with environmental loading) which may be less than the instantaneous stress required to produce immediate rupture. Generally, the lower the stress, the greater the number of cycles required to reach failure. The fatigue limit is the stress below which rupture does not occur irrespective of the number of stress cycles. However, when corrosion is present, fatigue life is considerably shortened and no fatigue limit exists.

Fatigue damage manifests itself as cracks at points of stress concentration. It is normally identified by the existence of cracks either side of the crack where failure actually occurs.

Early North Sea structures suffered from some design inadequacies and a lack of fabrication control. Feedback from operations has led to more accurate design assumptions and better quality control in fabrication yards. As a result of this, structures which have recently been fabricated are much less likely to suffer from fatigue damage and this should be borne in mind when assessing Figure 4.2.

Most bracing members and jacket nodes are subject to fatigue-inducing loading. Generally, the critical areas are the nodes in the wave zone and, to a lesser extent, at the inner faces of pile-to-jacket connections. It is generally recognised that the fatigue design of the conductor guide frames of early North Sea structures was deficient. As a result, many of these guide frames have experienced fatigue cracks at the saddle hot spot locations, and this has necessitated repair or strengthening.

Several widely reported failures of members have occurred recently at single-sided butt welds. This type of weld occurs mainly at brace/stub and chord/can connections or, less frequently, at access windows. Fatigue problems at these locations are particularly difficult to detect because the fatigue crack grows from the inside of the member outwards. Conventionally, rigorous fatigue analyses of these joints have not been performed during design or, where performed, have used the Class F2 S-N curve as recommended in the Department of Energy Guidance Notes[4.3]. It is now generally accepted that the Class F2 curve is very optimistic for this detail and that unrealistically long fatigue lives are predicted.

Locations with the highest fatigue risk are those where there is a combination of large cyclic stresses and welding defects, particularly if the member also carries a large static tensile load. These locations may be identified from a fatigue analysis for all members to compute their comparative lives (see Section 5.2); the locations with the highest risk of welding defects may be identified by examining the welding procedures and the post-welding NDT reports. For circumferential butt welds where repairs to the weld root have been conducted through access windows, it may be assumed that the weld itself is sound, having been converted into a double-sided butt weld, and that potential problems are confined to the window closure weld.

4.2.7 Seabed deterioration and seabed debris

The stability of fixed installations (and jack-ups) is affected by erosion (scouring) of the sea bed resulting from tidal currents and wave action. Such deterioration may be assessed by visual inspection using divers or ROVs.

Accumulation of debris on the seabed can cause problems especially if it is metallic (eg scaffold poles) and in contact with the structure as this will place an increased demand on the cathodic protection system. Debris also represents a significant safety hazard to divers and therefore should be removed prior to inspection work.

4.2.8 Damage to submarine pipelines

Damage to a pipeline is likely to represent a more serious problem than damage to a single member of a typical jacket structure because the pipeline has no redundancy and failure represents loss of production and the risk of loss of public confidence due to environmental effects, etc.

In-service inspection of submarine pipelines normally entails the problem of line length as well as access limitations, and surveys made of the as-laid condition prior to burial therefore represent an important source of information. Tables 4.3 and 4.4 summarise a review made of North Sea pipeline records[4.2]. Other reviews of pipeline damage are also available[eg 4.4] but most available data has been gathered from operational experience with land-based lines. The tables indicate that more damage has occurred during pipeline laying than during operation and the majority of this is in the form of buckles and gouges. External corrosion has been more troublesome than internal corrosion so far and it is significant that the corrosion problems have all occurred near platforms, perhaps indicating inadequacy of CP systems when adjacent to other large masses of steel.

Untrenched pipelines may lose parts of their concrete coating, leading to loss of pipeline stability, possible flotation and external corrosion. The cause of this damage may be:

- unsatisfactory installation
- vortex shedding over pipeline spans which have developed because of scour or poor seabed conditions (a pipe in this condition may also suffer fatigue damage)
- impact from trawl boards and anchors.

The main types of internal defects are corrosion and gouging. Both pitting and general corrosion have been observed and the rate of corrosion varies with the proportions of moisture and acid hydrocarbons present. Circumferential and axial gouging have been reported and, although the causes of these are not entirely clear, pipeline debris and high operating pressures (up to 140 bar) may be important factors.

Defects may also exist in the pipe wall as a result of manufacturing or construction procedures. An extreme example of such a defect was a mid-wall copper inclusion 50 mm wide, 4.5 m long and weighing 20 kg.

4.2.9 Damage to floating and other non-fixed installations

The major cause of defects in floating units is known to be poor fabrication standards. This is an historical problem; floating units were originally classed as ships and, consequently, fabricated to ship-building standards which are not as stringent as those required for oil and gas facilities in hostile environments. Fatigue damage has also occurred, generally as a result of poor joint detailing exacerbated by the sub-standard fabrication. Impact damage from ships and during relocation has also been reported.

Examples of types of damage specific to non-fixed installations are:

- wear at articulation hinges
- fatigue damage where mooring pegs are connected to a buoy
- wear on cables and on the installation where the cables enter
- link wear in anchor chains.

4.2.10 Unexpected defects

Although service experience assists in highlighting the areas in which structural problems are likely to occur, allowance should also be made in any inspection plan for unexpected circumstances, such as departures from the 'as-built' drawings. There was no record of the welded details on members subject to high fatigue loading which led to failure on the *Alexander Kielland*, Contingency inspections or monitoring should be planned to enable problems of this sort to be detected in time for corrective action to be taken before failure occurs.

4.3 MARINE FOULING

4.3.1 Introduction

Marine fouling can be considered as one of the forms of damage or deterioration that may affect offshore installations. Unless they are protected by effective antifouling measures, installations at any location or depth on the UK Continental Shelf will become fouled with marine growths[4.5]. On the UKCS, and indeed as a general rule, the rate of fouling development and its ultimate thickness decrease with increasing distance from the shore and with increasing depth at the location. Sites in shallow seas on continental shelves, exposed to currents rich in plant spores and animal larvae, are liable to suffer the greatest fouling. Conversely, areas of the Earth's oceans lacking larvae or spores are unlikely to yield significant levels of fouling. Such areas include Arctic and Antarctic seas, distant mid-oceanic sites in the Pacific and Atlantic and most bathyal regions, ie those where the water is greater than 1000 m in depth.

The most important data required from any survey of marine growth are figures for the average thicknesses of growth at each depth. Information is also likely to be required on the types and extent of the fouling species.

The fouling of any new surface begins as soon as it is immersed in the sea. It proceeds through a number of stages from a rapid colonisation by microscopic forms to a complex biological community with an ultimate predominance of certain types of microscopic organism. It is impossible to give a precise timing for the stages of fouling since the timing depends on many factors, such as geographical location, depth of the structure, season of the year, nature of the water mass and its temperature, and the precise nature of the immersed structure.

4.3.2 Effects of fouling

The structural effects of fouling are summarised in Table 4.5 and detailed below.

Obscured surfaces

All fouling contributes to a covering layer on steel (and concrete) surfaces. It usually has to be removed before visual inspection and non-destructive examinations of the substratum can be carried out.

Static loading

Most soft foulers (see Section 4.3.3) have a specific gravity close to that of sea water, and so contribute little to static loading. Only organisms with hard calcareous shells, plates or tubes are likely to add to weight loading, and the most important of these is the mussel. Mussel beds 60-mm thick on a typical horizontal framing of about 3500 m^2 might add 13 tonnes extra weight. This additional load is small in comparison with the weight of steel or the weight of anodes on fixed platforms, but may be much more critical for semi-submersibles or tethered buoyant platforms.

Hydrodynamic loading

Soft and hard growths contribute to an increase in hydrodynamic loading of members in three ways:

- increase in member dimensions
- increase in added mass of members
- increase in surface roughness.

Table 4.6 shows results from some experimental measurements on fouled cylinders of different diameters[4.6]. This data supports evidence from other measurements on cylinders with hard fouling showing that drag coefficients increase from 0.6 to about 1.2[4.5]. The effects of soft and hard growth are qualitatively and quantitatively dis-similar and no formulae exist for estimating an equivalent thickness of hard fouling from known thicknesses of a complex mixture of hard and soft growths.

Hard fouling is unchanged by water movement; its effective thickness and surface roughness remain constant. In contrast, soft growths bend to varying degrees in response to water movement, so their effective thickness and surface roughness change continually. In a mixed community of several species of soft growths, some will bend and wave in a current, some may bend flat onto the substratum and some will flex a little but remain more or less upright. This variable response presents an extremely complex picture which so far has not been modelled in tank tests. Calculation of the contribution of soft growth to loading is further complicated by uncertainty about which size parameter to use. For example, a dense stand of seaweeds may be 1 m high when the plants are stretched out fully, but will perhaps lie only 150 mm away from the substratum when a wave passes. The apparent increase in the diameter of a cylindrical member therefore lies somewhere between 300 mm and 2 m, but at present there are no data or guidelines to determine the exact magnitude of the effective increase. The few data available show that soft growths do contribute to hydrodynamic loading and that their effect is not negligible.

Physical damage to steel

Direct damage to steel caused by the settlement and growth of marine organisms is rarely seen on offshore structures although the side plates of barnacles can dig into some surface coatings.

Cleaning work carried out to remove the calcareous base plates of some species may cause superficial damage to steel surfaces as well. There are no recorded instances of significant damage resulting from the removal of marine growth – but the potential for damage does exist.

Corrosion

The general relationship between fouling and corrosion is not clearly understood. On the one hand, fouling may act as a barrier to the access of oxygen to a steel surface and so reduce corrosion, on the other it may be detrimental to the complete cathodic protection of steel by shielding it. In addition, the micro-environmental effects of oxygen concentration cells and pH concentration cells associated with fouling layers are not yet fully understood or quantified.

Many sacrificial anodes on a number of installations are extensively covered by fouling. It has been suggested that the fouling prevents the anodes working properly, thus compromising the cathodic protection. However, it may be that the anodes are not yet required, are not wasting, and so become fouled. When they are required to contribute, it is thought that normal wasting would begin and that the fouling would slough off. There is no evidence of significantly low CP voltages around extensively fouled anodes, and it is unlikely that fouling will prevent anodes from functioning as and when required.

Marine growth may provide conditions in which micro-organisms capable of damaging steel can thrive. The most important group of bacteria in this context are the sulphate-reducing bacteria (SRB) which are present in normal sea water but in a biologically dormant state. They become active and rapidly increase in numbers only in anaerobic conditions. Three micro-environments beneath marine growth are thought to be particularly suitable for high levels of SRB activity:

- beneath the calcareous base plates of some barnacle species
- beneath dense mats (or 'turfs') of hydroids – the root-like interwoven base structures of the hydroids tend to trap drilling mud, silt and detritus and this layer quickly becomes anaerobic
- beneath dense mussel beds – in the silt and mud trapped among the threads that bind the mussels to the substratum.

In addition to these micro-environments created by marine growth, there is good evidence to show that the environment beneath thin layers of drilling mud, particularly oil-based drilling mud, is conducive to the rapid growth of SRB. The zone of high SRB activity would be a layer 10–30 mm thick immediately below a 10 mm thick aerobic layer from which the SRB would obtain nutrients and sulphate.

The presence of a highly active SRB population on a steel surface poses a risk of biological corrosion (although conclusive evidence that it does occur has not so far been found). It would manifest itself by pitting of low-carbon steel, graphitisation of cast iron or hydrogen cracking and blistering of steel.

SRB-induced corrosion is especially likely to occur where areas of steel are exposed to the active SRB zone for a long period of time, eg where seabed sediments at the base of a leg remain stable and are not periodically disturbed by currents.

4.3.3 Types of fouling

Many varieties of plants and animals are found on offshore installations in the North Sea; more than 29 species of seaweeds and 60 species of animals have been recorded from a single platform[4.7] although a dozen or so species or types have been found to constitute the bulk of marine growth cover. All the species described below are sessile (ie remain in one place for their adult lives). They are important primarily because on many installations they cover large areas, are themselves large and may be long lived. Some of them are members of the initial fouling community that forms in the first 2–3 years of a fixed installation's life. Others are part of the later fouling community that may appear 5–8 years after immersion and may persist unchanged for many years after that.

In the North Sea it is usual to find different characteristic fouling communities growing at different depths on offshore installations. Shallow regions from the splash zone to 15 m deep are usually dominated by a mixture of mussels and seaweeds overgrowing a background cover of tubeworms and saddle oysters. From 15 m to about 80 m, the dominant organisms are soft corals, anemones and hydroids. The fouling layer from 80 m to the sea bed consists of a mixture of solitary and aggregate tubeworms, barnacles, sea-squirts, hydroids and soft corals.

In addition to the fixed, macro-fouling species there are a large number of mobile animals such as crabs, starfish, worms, snails and shrimps but these are generally insignificant in terms of the integrity of the structure and its inspection.

The major types of macro-fouling seaweeds and animals of the North Sea are described below; more details of these and of fouling species from other parts of the world may be found in Reference 4.6.

Seaweeds

Seaweeds are plants that require sunlight for their existence. In the North Sea they are therefore confined to the depth zone from about 2 m above sea level to about 15 m below it. In simple terms, the bodies of the plants consist of three parts: the holdfast (a root-like structure that anchors the plant to the substratum), a stalk and leafy fronds. Brown kelps may reach lengths of more than 3 m; they increase in size from year to year, and individual plants may live for 10 years. Although large and tough, kelps may be completely eradicated by cutting through the stalk; the holdfast will not regrow another plant.

Hard animals

The animals that attach themselves to offshore installations may be divided into two groups: hard foulers and soft foulers. Hard foulers possess a rigid and hard external skeleton in the form of a shell, tube or plates, which protects the fleshy body within.

By far the most important hard fouler is the bivalve mussel *Mytilus edulis*. The body of this animal is protected by a hard calcareous shell consisting of two valves hinged along one side. Specimens up to 90 mm long have been found offshore. Mussels were originally carried offshore as tiny spat originating from nearshore populations, and are now present on most jackets. Several installations have large populations of adults which themselves are producing spat, which may in turn colonise other structures. Mussels are naturally adapted to settle in the intertidal seashore, and are therefore found at shallow depth offshore. Horizontal framings in the depth range 0–20 m, with their small-diameter horizontal members and complex geometry of conductor guides, are particularly attractive sites for mussel settlement. Mussels beds composed of large numbers of closely packed individuals may become established within two years of immersion of the installation and steadily grow in extent and thickness. See Figure 4.3. Beds in excess of 200 mm thick have been found on structures in the southern North Sea and in excess of 150 mm thick in the northern North Sea. Mussels are well able to withstand storms and wave action; individuals attach themselves to a substratum and interlink to each other in a bed by means of strong, proteinaceous threads secreted by the body. Each thread ends in a pad which is cemented to the substratum, and the radiating threads provide a tough, elastic anchor that is able to absorb sudden tension and is extremely difficult to break.

Other hard foulers commonly found in the intertidal coastal zone, and now present on some offshore structures, are shallow-water barnacles. They are found offshore in the depth range from the splash zone down to about 20 m and in sizes up to 30 mm basal diameter and 40 mm high. The soft tissues of the barnacle body are protected by a cone-shaped case of interlocking calcareous plates, which is cemented to the hard substratum. Barnacles settle in close proximity to each other, thus creating carpets of densely packed individuals. Even after death, the empty cases may remain attached to the substratum and become overgrown with secondary fouling organisms.

The deep-water barnacle *Balanus hameri* is found on nearly every offshore platform in the North Sea (see Figure 4.4). Rarely found above 30 m it is common below 60 m and has an extreme depth range to 210 m. It achieves a basal diameter of 50 mm and a height of 50 mm after about seven years growth. The animal itself can be removed without too much trouble but this leaves a hard calcareous base plate behind, very firmly attached to the substratum. The base plate is invariably left behind by any superficial cleaning and requires much more vigorous action to remove it.

The final group of hard fouling animals are the tubeworms – soft worms that secrete and live in hard calcareous tubes cemented onto the substratum. They are found throughout the depth range of the North Sea and most are solitary species which, nevertheless, may be found growing in large numbers together. Their tubes are about 5 mm in diameter and may reach 100 mm in length. The worms usually live for about 18 months, but empty tubes remain attached long after the animal has died and provide a rough, hard surface for the attachment of later fouling species. Vigorous cleaning is required to remove all traces of the tubes.

There is a species of aggregate tubeworm, most commonly found at depths greater than 60 m, although it has been found at 30 m offshore and it has a recorded depth range to 550 m. Individual tubes of this species are no more than 1 mm in diameter and 50 mm long, but the worms' habit of aggregation means that many thousands of individuals grow in intimate proximity cemented to each other and the substratum. See Figure 4.5. Colonies can be in the form of flat 'reefs' 20 mm thick and 300–500 mm diameter or hemispherical domes of the same diameter but up to 200 mm high. The domes are liable to damage and easily broken but the tubes cemented to the substratum are firmly attached and difficult to remove.

A number of potential fouling species are found on the UK Continental Shelf at depths greater than the sites of existing installations. Stony corals may be of particular concern; they are hard, slow-growing, long-lived animals which attain greatest abundance in the depth range 200 m to 500 m. It has been suggested that any installations at great depth on the Continental Shelf, particularly to the west and north of Scotland, will become fouled by these animals[4,8].

Soft animals

The term 'soft animals' is somewhat misleading – their textures vary from type to type. Some of these creatures form stiff, unyielding growths even though they have no hard, external skeleton.

The most common type of soft animal offshore is the hydroid, a colonial animal that forms soft, flexible, plant-like growths (see Figure 4.6). Hydroid species range in size from less than 50 mm in length, to tall, erect species which may reach 150 mm. Hydroids are found throughout the depth range of the North Sea, and are particularly conspicuous in the early years of a platform's life since they are a major part of the initial fouling community. As fouling communities age and change in character, they may be replaced by other macro-fouling species, but they may still be important foulers below 100 m depth because other foulers are less abundant there. References by divers to 'seaweed' at 100 m and below invariably refer to hydroids; seaweeds do not grow at these depths in the North Sea. Hydroids are attached to the substratum by a surface anchor which is not invasive, though fine cracks and defects are exploited.

Plumose anemones attain greatest density offshore in the midwater depth range from 30 m to about 100 m. They consist of a fleshy body trunk bearing a ring of tentacles on the upper end. Their shape and size can change considerably from elongated body and open tentacles to a rounded mound. Individuals up to 200 mm long have been found offshore and densities in excess of 300 individuals per m^2 have been observed (see Figure 4.7). The animal anchors to the substratum by a flattened pedal disc at the lower end of the body, which firmly grips the substratum by suction. Anemones normally remain in one place, but they can change position very slowly by gliding along on the foot.

A more rigid soft animal fouler which also attains maximum abundance in the depth range 30 m to 100 m on offshore installations is a soft coral commonly called 'dead man's fingers'. It is found on most structures, even those furthest from land, and densities may exceed 500 indiviudals per m^2. The stiff body of this colonial animal is roughly cylindrical and is usually branched with one or more rounded lobes. Individuals with basal diameters of 80 mm to 100 mm and heights in excess of 200 mm have been found offshore. The animal is anchored by a spreading basal disc whose cells achieve intimate contact with the substratum. See Figure 4.8.

The last common group of soft animal foulers are the tunicates, or sea-squirts (see Figure 4.9). Solitary species with body lengths of 30–60 mm may be found at depths down to 300 m. Sea-squirts prefer to live in sheltered, silt-free conditions, such as on the undersides of horizontal members of offshore structures.

Table 4.1: *Summary of underwater inspection findings for 21 steel jackets in the North Sea*[2.5]

Type of defect	Number of platforms with the defect
Crack confirmed	12
Propagating crack	3
Dented member	15
Deflected member	11
Low CP potential	10
Missing anode	9
Defective anode	4
Loose anode	7
Pitting corrosion	20
General corrosion	2
Burn mark	4
Heavy marine growth	13
Wire chafe	18
Scour	1
Debris	21

Table 4.2: *Checklist to identify potential failure mechanisms*

Failure mechanism	Promoting agent	Type of damage	Location in structure
Member buckling and plastic collapse	Compressive loads Geometry (slenderness ratio in imperfection-sensitive range) Impact damage Overload	Member dents General evidence of abnormality	Compressive members with high utilisations Members suffering from impact/ installation damage or subject to exceptional loadings (eg from drilling cuttings)
Joint failure (static load)	Impact damage Overload Fabrication errors	General evidence of abnormality	Joints with high utilisations Joints of members subject to buckling/plastic collapse (see above)
Fatigue	Cyclic loads Stress raisers Initial defects	Fatigue cracks Flooded members	Low nominal fatigue life members and joints (especially in splash zone) Poor fatigue details (eg single-sided butt welds and rigid appurtenance supports)
Fracture	Cracks (either fabrication or fatigue) Tensile stresses Residual stresses Low-toughness materials	Cracks Flooded members	Welds in tension members
Hydrostatic collapse	Hydrostatic pressure Tubulars with high diameter/thickness ratios Dents	Dents General evidence of abnormality	Thin-walled members at base of structure
Corrosion	Ineffective cathodic protection High-hardness microstructures	Pitting and 'knife line' attack Loss of wall thickness	Welded joints Flooded members Structure adjacent to CP current drains (eg pile guides)

Table 4.3: *Submarine pipeline failures discovered after laying but prior to start-up*

Type of failure	No reported
Buckles and gouges*	15
Anchor wire	3
Floating	1
Pigs stuck	4
Pressure test	3
Others	1
Total	24

** Probably caused by anchor or trenching sledge*

Table 4.4: *Number of pipeline incidents during operation needing remedial action*

Type of damage	No of incidents			
	Near shore	Open sea	Near platform	Total
Anchor damage	1		3	4
Corrosion			4	4
Stability	3		1	4
Pinhole		1*		1
Creep/thermal			3	3
Cause unknown			1	1
Total	4	1	12	17

** Detected during pressure testing*

Table 4.5: *Summary of the effects of marine fouling organisms on offshore steel structures*

Organism	Effect				
	Surfaces obscured	Weight loading increased	Hydrodynamic loading increased	Physical damage to steel	Microbial corrosion of steel
Soft growths					
Seaweeds	•	–	•	–	–
Kelps	•	–	•	•	•
Anemones	•	–	•	–	–
Soft corals	•	–	•	–	–
Sea squirts	•	–	•	–	–
Hydroids	•	–	•	–	•
Bryozoans	•	–	–	–	–
Sponges	•	–	–	–	–
Hard growths					
Mussels	•	•	•	–	•
Tubeworms	•	•	•	•	–
Barnacles	•	•	•	•	•
Oysters	•	•	•	–	–

Table 4.6: *Drag and inertia coefficients for various types of fouling on cylinder surfaces*

Nature of cylinder surface	Mean equivalent diameter (mm)	Mean drag coefficient	Mean inertia coefficient
Clean, smooth	200	N/A	1.08
Clean, smooth	400	0.49	1.14
Clean, roughened	200	N/A	1.22
Clean, roughened	400	0.78	1.17
0.5 m long kelp – 100% cover	≈500	1.67	1.99
1.0 m long kelp – 100% cover	≈520	1.69	2.13
Single layer of mussels – 100% cover	455	1.20	1.32
Multiple layers of mussels – 100% cover	285	1.85	1.50
Multiple layers of mussels – 50% cover	N/A	1.68	1.59
Multiple layers of mussels – 25% cover	N/A	1.56	1.32
Sea anemones and squirts – top and bottom covered	≈365	1.09	1.17
Sea anemones and squirts – sides covered	≈365	1.35	1.08

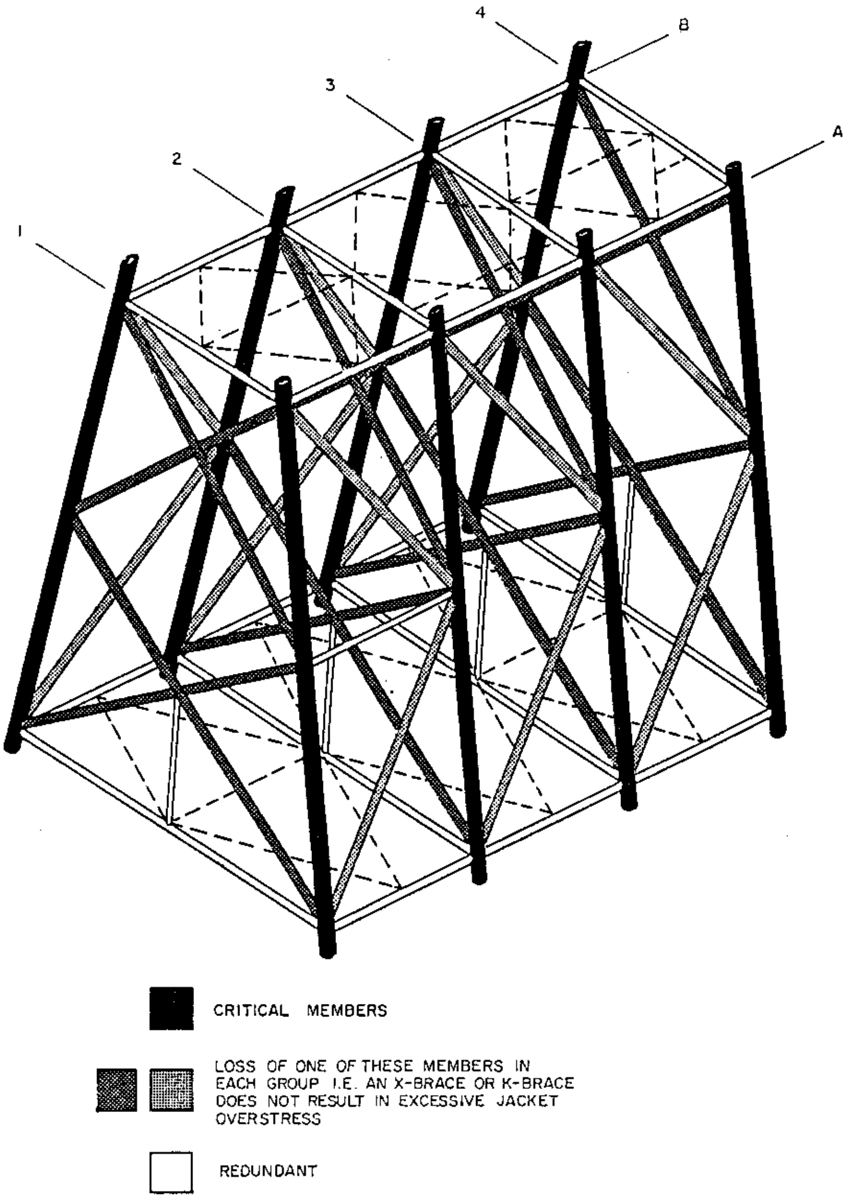


Figure 4.1: *Hypothetical jacket structure indicating which members can accommodate most damage and deterioration*

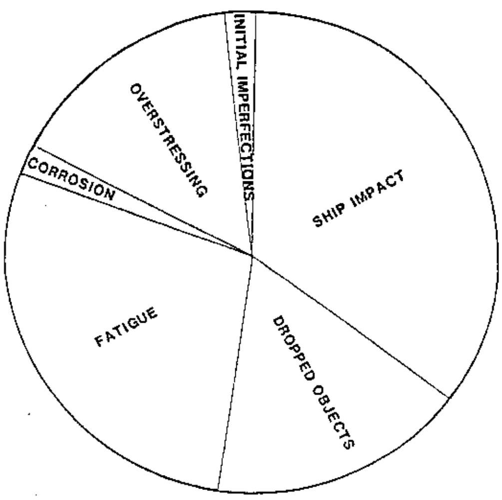


Figure 4.2: *Causes of damage to North Sea fixed platforms that resulted in repairs*

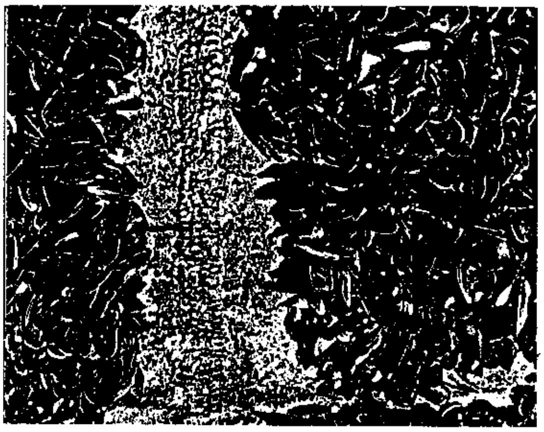


Figure 4.3: *Mussel fouling*

Figure 4.4: *Deepwater barnacle fouling*

Figure 4.5: *Aggregate tubeworms*

Figure 4.6: *A 'turf' of hydroids*

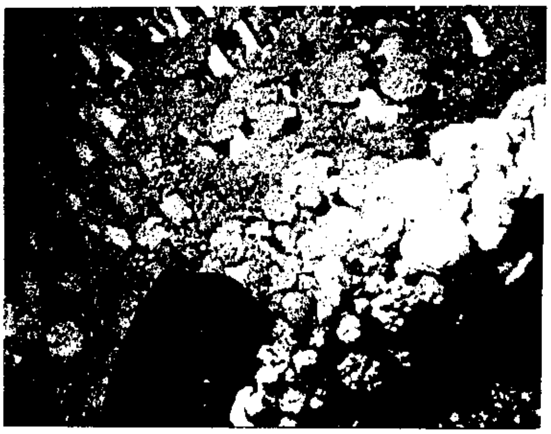


Figure 4.7: *Anemones*

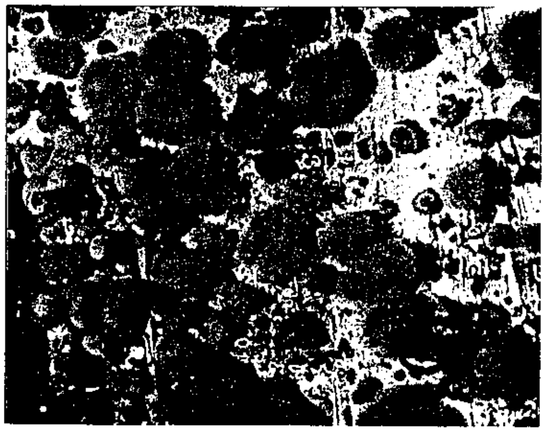


Figure 4.8: *Soft coral fouling*

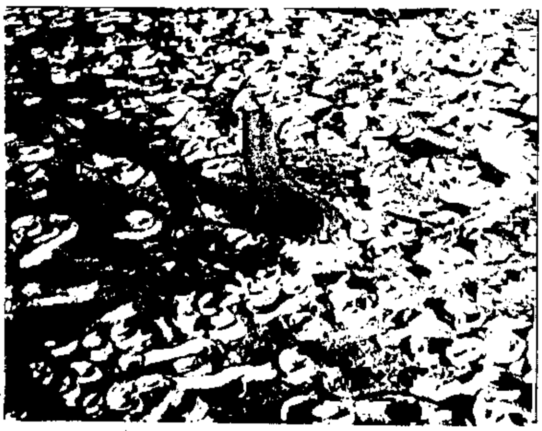


Figure 4.9: *Sea squirts*

5 Management of inspection planning

5.1 INTRODUCTION

There are alternative approaches to the planning of routine underwater inspection programmes that provide a greater degree of reliability than the traditional approach described in Section 2.5, which is primarily governed by statutory requirements, nominal fatigue lives and the likelihood of ultimate failure of the components inspected.

In this chapter, the rational approach to the optimisation of underwater inspection that was introduced in Chapter 3 is developed in some detail for a steel jacket structure, the most complex offshore installation for which inspection programmes are required. The principles described here can be adapted to other types of structures with appropriate simplifications and modifications (see Section 5.7). Although it is inevitable that some judgements will be subjective (the reasons for this are discussed below), the format adopted attempts to maximise objectivity in planning for inspection.

The rational approach aims to cover all of the major items having a bearing on underwater inspection, and as a result is rather complex. Operators may choose to implement only those aspects of the approach deemed to be most important; these alone should represent a considerable advance over current practice. Other aspects can then be introduced progressively, until the complete approach is in place.

The method requires a considerable quantity of data to be processed when planning the underwater inspection, and it is recommended that a computer database should be established to manage this. A microcomputer would be adequate for most structures if a simplified version of the total approach were to be implemented. This would lend itself naturally to the points systems proposed for inspection priority ranking.

It is emphasised that this approach is for *inspection planning*. Damage discovered during an inspection should *always* be assessed, possibly using the methods described in Chapter 8. After an assessment, a decision on whether to repair and what revised inspection strategy should be adopted for future inspection of the damaged or repaired component are fed back into the inspection planning database developed here. The approach also uses damage-assessment techniques to rationalise inspection plannning; components considered critical to the integrity of the complete structure can be assessed to determine the effects of damage *before* damage occurs. An understanding of the development of a postulated defect in a component will have an important impact on the strategy adopted for its inspection.

5.1.1 Objectives of the approach

The principal objective of any inspection plan is to provide a level of reliability which is commensurate with the consequences of failure (see Section 2.1). If a new approach to inspection planning is to be implemented, it must also satisfy the following criteria:

- there should be no reduction in the level of confidence in the integrity of the structure
- either cost or risk should be reduced compared with the original approach.

Little purpose is served in implementing any new approach to inspection planning which does not meet these objectives.

5.2 PRINCIPLES OF THE RATIONAL APPROACH

5.2.1 General

This rational approach to the optimisation of underwater inspection is shown as a flowchart in Figure 5.1. The flowchart portrays the principal considerations which have a bearing on the inspection programme and their relationship to each other. In this section, the major concepts are introduced and discussed, and the method of incorporating them in the inspection plan is demonstrated.

The development of the approach is discussed in Section 3.2 where it was concluded that an 'optimum' inspection plan would be based on consideration of the following criteria:

- consequence of damage
- failure mode

- likelihood of damage
- cost and reliability of inspection.

The first and third criteria in this list are linked through the concept of fracture criticality. If the consequences of damage in a specific component are crucial to the integrity of the whole structure and if the component is likely to experience damage, then the component is said to be 'fracture critical'.

Attempts to be wholly objective in the planning of an inspection programme encounter the following problems:

- *Size limitation*
  It is immediately apparent that an almost infinite set of damage scenarios, including combinations of different sorts of damage, can be postulated.
- *Loading regime*
  The loading regime in each major component would be generated as a matter of course during the design process but whether or not a component is fracture critical may be a function of relevant loading combinations. For example, if a member acts in compression for 90% of its life but comes into tension only occasionally during storms from a particular direction, the member cannot be simply classified as a tension or a compression member.
- *Practical considerations*
  The practical considerations that inspection planners need to address include:
  - specification and location of the diving support vessel
  - diving requirements
  - cleaning requirements and methods
  - cleaning time
  - inspection methods
  - time taken to inspect.

If the objectives listed in Section 5.1.1 are to be met, a combination of objective and subjective decisions is inevitable in the planning of a routine inspection programme, but it is necessary to maximise the objectivity and use the best information possible in making the subjective decisions.

The overall strategy is to develop an inspection priority ranking system to be used as a tool by the inspection programme planners.

5.2.2 Philosophy of inspection, maintenance and repair

Although the basic principles behind the optimisation of underwater inspection are relatively well defined, they may be implemented in a number of different ways, reflecting the operating procedures of each installation operator. The operator's approach to a number of different aspects should be clearly defined before attempting to implement the inspection plan. Aspects to be considered are included in the following list:

- *The degree of optimisation desired*
  The operator should establish his position as to whether a highly optimised inspection plan is desired, or whether the level of inspection should be determined primarily by statutory requirements.
- *Balance between cost and reliability*
  The operator should determine whether he wishes to implement a lowest-cost scheme, or whether he is prepared to accept increased costs in exchange for additional reliability.
- *Importance attached to analytical predictions*
  The inspection programme may be planned largely on the basis of analytical predictions of where to inspect and with what frequency. Alternatively, the planning may be based primarily on empirical rules. The operator should establish the degree to which the results of analytical studies will be incorporated into the planning of the inspection programme.
- *Balance between planned and contingency inspections*
  Even when the total inspection effort is planned in accordance with predictions of where the effort should be directed, some inspection must be done on a contingency basis (ie random inspections). The operator should establish the balance that he wishes to strike between these two approaches.

The operator's overall approach to inspection, maintenance and repair should be formulated by the review panel (see below), and should be incorporated in a policy document which acts as a guide for the implementation of the inspection programme.

5.2.3 Review panel

Accepting that subjective judgements are an inevitable part even of a rational approach to inspection planning, an expert review panel is proposed. It should contain, as a minimum:

- structural design specialists
- quality assurance specialists
- inspection specialists
- diving specialists.

It is probable that there will also be specialist metallurgical and corrosion input and possibly input from the certifying authority.

The functions of the review panel are:

- to provide, from calculations and experience, input into a rational plan for assessing the importance of inspection of each component
- to decide which components from a priority listing of all components should actually be inspected
- to advise on inspection methods
- to liaise with the certifying authority
- to draft and revise written guidance on:
  - the overall philosophy of inspection, maintenance and repair
  - the approach to inspection planning
  - rules to be followed in making subjective judgements.

It would be very beneficial if the same group were responsible for the offshore inspection management. Suitable quality and reliability audit by outside specialists would also be appropriate. It is suggested that members of the panel serve for an agreed minimum period with overlaps between personnel changes to ensure continuity and consistency.

5.2.4 Inspection priority ranking

A rational basis is required for the review panel to be able to assess the importance of inspection of each component of the structure under consideration.

Section 2.8.4 described a 'ranking tree' approach which indicates the inspection priority of a component as a function of its probability of failure and the consequence of its failure. This approach provides a useful method for the designer of a new structure to ensure inspection, maintenance and repair costs are minimised. Inspection planning for a real structure is more complex and a more sophisticated approach is required. The inspection priorities derived from a ranking tree approach vary little from year to year; hence an additional mechanism is needed to help decide which of the critical components *should be inspected in a given year.*

The assessment of importance of inspecting component j in a given year n is a function of:

- consequences of damage
- mode of failure
- likelihood of failure
- cost and reliability of inspection
- inspection history to date
- certification requirements.

Although a ranking tree could be developed which accomodates all of the above, a points system is also needed to quantify the rankings. Analysis can then define the relative importance of inspection for each component at any time. Judgement has to be made on some aspects of the ranking (eg the *relative* importance of when the component was last inspected) so that the outcome is a mixture of objective analysis and subjective judgement.

The basis of the proposed points system for this rational approach is summarised in Figure 5.2. For a component j, the weighting for consequences of failure, Y_j, is the sum of a number of individual weightings representing parameters such as the redundancy of the component and the immediate risks to life if it fails. Similarly, the numerical weighting for liklihood of failure, X_j, is the sum of individual weightings, this time representing items such as fatigue category and whether or not a defect is known to exist in the component.

The criticality rating of the component is the product of X_j and Y_j, but the overall inspection weighting is further influenced by the time elapsed since the component was last inspected. It is therefore proposed that the overall inspection weighting, Z_j, of each component of the structure at any specific time is represented by:

$$Z_j = (X_j \times Y_j) + W_j$$

where X_j is the weighting for liklihood of failure of the component

Y_j is the weighting for consequences of failure of the component

W_j is the weighting representing the inspection history of the component.

It is suggested that the inspection weightings should be assembled on a conventional computer spreadsheet database for all components in the same category (joints, members, etc). The subjective and objective weightings for each individual input parameter in the overall weighting would be permanently exposed in the spreadsheet and the effect of changes in any input values could be assessed at the touch of a few buttons. The spreadsheet will provide the review panel with a simple working tool, defined as objectively as possible but capable of estimating the effects of the judgements they may be proposing to make in planning the inspection programme for a given season.

The approach implies, rather than an inspection cycle, a unique programme each year designed on the basis of all available information. During the planning of the inspection programme for year 1 in the life of a specific structure, an initial ranking of components is carried out on the basis of their overall inspection weightings. This will highlight the components worthy of special consideration. The likelihoods and consequences of failure of these components should be investigated immediately (see Section 5.2.5 below) and, where appropriate, new weightings will be assigned as a result. This revised ranking table is used to plan the first inspection programme but the weightings will alter thereafter in the light of actual inspection findings. In this way, new priorities for inspection of components will be highlighted each year.

Simplification may be necessary before this whole approach is introduced fully. Currently, certification authorities require that a programme broadly covers, as separate inspection areas:

- corrosion condition
- fatigue condition (joints and members)
- member condition
- marine growth condition
- scour.

As a first stage in simplification, a set of categories such as these should be defined and treated for review separately until the rational inspection planning system is fully functional. Strictly speaking, the considerations of certification requirements are irrelevant to the development of an *optimised* approach to inspection planning. Nevertheless, the certification system is an important part of the quality plan, and development of an optimised approach in conjunction with the certifying authority would be rational.

5.2.5 Detailed studies to optimise the weightings and ranking

It may be appropriate to conduct detailed studies to assist in refining the inspection planning. They should be considered either for components which have a high criticality rating (ie high value of $X \times Y$) where the objective would be additional safety, or for components which are expensive to inspect, where the objective would be cost savings.

The rate of return on investment in study would decrease for components with lower criticality ratings. It is suggested that the cost effectiveness of studies on the most critical components is assessed by realistic case studies before progressing to less critical components. The assessment studies would be based on postulated damage, would be performed for the purposes of optimisation, and would be undertaken before performing the inspections. They should not be confused with studies conducted after inspection when a defect has been found, where the main objective would be to assist in a repair-no repair decision.

Typical studies which might be performed are:

- *Redundancy*
  A preliminary assessment of redundancy would be made on the basis of engineering judgement by an experienced jacket designer. More detailed studies would require a computer analysis (see Section 8.5). Redundancy studies have become common for bracing members in the splash zone that are vulnerable to boat impacts.
- *Refined fatigue analyses*
  Refinements may be made to improve the accuracy of the S–N fatigue analysis used as one the imputs to the weighting for likelihood of failure of a component, X. Typical measures would include finite element studies to determine SCFs for joints which are inadequately represented by parametric formulae and the use of influence coefficients to account for the net stress effects of the loadings in all members meeting at a joint. These detailed studies would typically also investigate the variation in fatigue life around the joint, with a view to zoning any inspections.
- *Fracture mechanics studies*
  Fracture mechanics studies could be conducted to investigate crack growth and stability characteristics (see Sections 8.3 and 8.4).
- *Dented member studies*
  Dented member studies are traditionally applied to assess dents after they have been detected in an underwater inspection. However, there is a strong case for using them as a tool to identify members in which the strength is reduced disproportionately by minor dents. Suitable candidates would be compression members with slenderness ratios in the imperfection-sensitive range and compression members in locations exposed to impacts from vessels or dropped pbjects. Methods of performing dented member studies are detailed in Section 8.2.
- *Preventative maintenance (strengthening)*
  Strengthening may be considered for components where the cost of reliable inspection is high. If strengthening is to be carried out, the decision should be taken early in the life of the structure, to maximise the benefits of the reduced inspection requirements. If the strengthening is applied before any damage has occurred to the original structure, a full load-sharing design may be adopted, with consequent reductions in weight and cost. For this design approach, it may be required that the original structure remains unobscured by the strengthening so that it can be inspected during future inspections.

Following these detailed studies on specific components (or on sets of similar components), revisions can be made to the weightings of relevant individual parameters affecting the likelihood of failure, X, of a component and the consequences of its failure, Y. The effect of these changes on the overall inspection weighting, Z, of each component can be assessed through the computer spreadsheet described above and the components reranked for inspection priority.

5.3 PRACTICAL FACTORS AFFECTING THE WEIGHTINGS

5.3.1 Preliminary weightings

The first step in assessing the overall inspection weighting of each component in a structure is to divide the components into inspection groups. For a jacket structure, these might be:

- inspection group 1 – members
- inspection group 2 – joints
- inspection group 3 – foundations.

For each group the next step is to obtain the weightings for consequence and likelihood of damage for each component (ie their criticality ratings). For a new structure, the inspection history (the other factor affecting the overall weighting) is irrelevant, so inspection weighting is identically equal to criticality rating.

5.3.2 Consequences of failure

The concept of consequences of failure is closely associated with structural redundancy, and with other considerations which may be difficult to quantify. A points weighting scheme applicable to a joint to assist in quantifying the consequences of failure is tentatively proposed in Table 5.1. A similar scheme could be developed for other groups of components.

The first action in applying this scheme is to classify the structural component under consideration as primary, secondary or tertiary, according to its duty (item A in the table). Primary components includes the main legs and piles, major bracing members and principal members in the module-support frame. The conductor ladders and components required for installation purposes only (launch runners, etc) would be classified as tertiary, with most of the remainder of the structure as secondary.

The next item to assess is the redundancy of the component. When applying the test to a brace member at a joint, it is important to assess the redundancy of both the brace member itself (item B) and, at the same time, of the chord (item C). Both members should be considered together in this manner since loss of the brace may also involve significant damage to the chord.

The concept of likelihood of other short-term losses (item D) refers to the case where loss of a component immediately causes consequential damage. Failure of one component may cause a portion of the structure to fall which, in turn, may cause impact damage on lower portions of the structure and may involve costs for recovery of the components involved.

The concepts of immediate risk to life (item E) and immediate risk to the environment (item F) are probably more difficult than any others to quantify. Some guidance on the way in which they may be handled, in connection with the derivation of suitable factors of safety for design codes, may be found in Reference 5.1. The types of component which would involve a risk to life are mainly associated with topsides structures or with a significant release of energy (tethers, prestressing bars, high pressure lines, etc).

The items concerning immediate risk of lost production (item G) and cost of repair (item H) are easier to quantify, because they can be measured in financial terms.

The weighting for confidence in the assessment (item I) would normally be given a medium weighting in a new structure unless the component under consideration is not represented in the structural analysis model, in which case the low weighting (ie a high numerical value) would be applied.

The first assessment of the overall weighting for consequence of failure based on these individual input items is inevitably largely subjective. Item A is linked strongly with items B, C and D to give the designer's assessment of the component's fracture criticality. Items E to G address risks other than structural as a result of damage to a specific component and would normally score a medium weighting. Examples of exceptions are damage to risers, which would score high under F and G, and loss of a module-support frame which would score high under E.

An obvious danger is that different people will make different subjective judgements for the individual input items in identical situations. This must be minimised by:

- making written guidance on how to assess each item
- ensuring that one person makes the final judgement for any one item on all components.

For example, one engineer should make the assessments for the degree of redundancy of all components in a group. It is less important that a different person might make all the judgements on, say, immediate risk of lost production. Although this might alter the emphasis of these risks relative to the structural considerations, the overall ranking of the weightings will be little affected. The rules for weighting should be included in the written guidance produced by the review panel (Section 5.2.3).

As a result of all these assessments, an 'average' component should score a weighting of 80 for the consequences of failure part of the overall inspection weighting. More critical components will score higher.

5.3.3 Likelihood of failure

Chapter 8 gives a detailed discussion on the methods of determining the likely modes and locations of structural failure. For each location, and therefore each component, the relative likelihood of failure can be quantified using the points system tentatively proposed in Table 5.2.

The likelihood of failure of a component is a function of damage due to:

- design life and time in service
- material quality

- fabrication quality
- rate of corrosion
- existing defects
- marine and platform operations.

Most of these factors are accounted for in design and, as a corollary, a well designed structure can expect no damage during its design life other than from random accidental damage. Of course, this expectation must not be taken too literally and studies prior to commencement of a lifetime inspection programme will be effective in identifying areas most worthy of attention (ie high consequence of failure components).

To predict the fatigue category of joints for Table 5.2 (item K), the conventional technique described below is proposed as a first cut. The fatigue categories of all members, on the other hand, would be medium except for those with access windows or appurtenance connections which would be high.

For a new structure, the confidence in the assessment (item S) would be medium for all components unless the component is not represented in the structural analysis model, in which case a low weighting (high numerical value) would be applied. If detailed studies (see Section 5.2.5) are carried out, the weighting on item S may be reduced so that a component is placed in a high or medium category, ie high or medium confidence in assessment.

Fatigue life: use of conventional technique

Older structures in the North Sea have encountered damage, particularly from fatigue, which had not been anticipated in design. This has led to improvements in the approach to fatigue design and recent studies have shown that structures behave reasonably well according to the expectations of an S–N curve type reanalysis. Nevertheless, the level of experience of the engineer carrying out the reanalysis is crucial if a structural model is to be produced that will accurately identify the areas susceptible to premature fatigue. In addition, real fatigue cracks are often the result of poor fabrication practice or poor materials, or are found at locations simplified in the fatigue analysis (eg the derivation of SCFs by parametric equations). Consequently, fatigue analyses should only be taken to provide guidance.

For the purpose of assessing the weighting value of fatigue category (item K) fatigue considerations must be rationalised to a manageable size. The suggested first cut approach is:

- execute global fatigue analysis
- identify other areas in the structure susceptible to fatigue but excluded from global analysis (eg access windows in braces and appurtenance connections)
- categorise components into broad classes, eg:
  - high weighting value (in Table 5.2): fatigue life $\leq 0.5 \times$ design life
  - medium weighting value: $0.5 \times$ design life $\leq$ fatigue life $\leq 5 \times$ design life
  - low weighting value: fatigue life $\geq 5 \times$ design life
- carry out more detailed fatigue analyses (eg finite element shell analyses) on complex joints in the high category. It is worth remembering that if a high category component can be reclassified into the medium category as a result, then the analysis cost will almost certainly be outweighed by savings on a single inspection of that component. It is therefore proposed that finite element studies are executed *before* planning future inspections, and certainly before damage is discovered.

Fatigue life: use of advanced techniques

The discussion above relates to computation of design life on an S–N curve basis. The technique assumes that the safe limit of a crack is reached when it propagates through the thickness of the component. In fact, the actual development of a crack, usually initiating at a surface defect or defects, does not cause 'failure' until it has progressed to a point where the component can no longer sustain the static loading required of it, ie until it is unstable.

Techniques based on fracture mechanics (FM), discussed in Chapter 8, offer a more systematic approach to assessing the course of crack development. The ways in which a crack develops during different parts of its life vary according to geometry, loading and material properties. What the inspection planner needs to know is 'when must I inspect to ensure that I identify a crack (and have time to execute remedial procedures) before component failure?' rather than 'when must I inspect to ensure I identify a crack before it goes through thickness?' The discussion in Chapter 8 demonstrates that confidence in

FM-based answers to the first question is improving as the techniques are benchmarked against relevant test results, but that there are still few data on the behaviour of tubular joints after through-thickness cracking.

In practice, it is unrealistic to postulate all possible cracks and calculate their probable growth rates and stability. For the purpose of assessing item K in Table 5.2, it is proposed that the approach described as 'first cut' in the sub-section above is followed, and that detailed FM analysis is only carried out on components where premature cracks are anticipated *and* where the consequences of failure are serious.

Other damage

Although much of the testing work to support the design of structures fabricated from tubular components has been retrospective, service experience of static load failure due to real loading is very small. This is no cause for complacency; the behaviour of tubular joints is complex and some early design assumptions have now been shown to have been unconservative. Nevertheless, it is reasonable to assume that structures designed to current standards are unlikely to fail under static loading other than from:

- exceptional loading – eg earthquake or impact loadings, temporary or permanent increases in topside loading, and unexpected marine growth (item R)
- inadequate corrosion protection or allowance (item O)
- faulty materials or workmanship (items P and Q).

If the inspection planner has reason to doubt the quality of some components of the structure, higher weightings can be given to their inspection priority.

Types of damage are described in Chapter 2. The most common type of damage to date other than fatigue has been damage from impact, either from ships or from dropped objects. Primary components (item A in Table 5.1) susceptible to impact damage could be assessed for redundancy, and methods are discussed in Section 8.5. It is almost certain, in view of the infinite range of damage that could be caused in this category, that the inspection planners would opt to carry out systematic damage assessment only when a component is found to be damaged, with a view to planning the subsequent repair and inspection strategies. The likelihood of failure in the light of the damage would be assessed as well as the consequences. The likelihood is a function of the type of damage, load regime and possible failure modes of the component.

For the case of ultimate load failure, there is generally little evidence of distress until local failure occurs, and this may be detected by general visual inspections or by structural monitoring (see Sections 7.2 and 7.5 respectively). Failures of this type are usually caused by exceptional loadings, such as by boat impact or from dropped objects. Inspections should therefore be carried out as soon as an incident is reported or if evidence such as unexplained debris on the sea bed is encountered.

Random defects

There are statistical uncertainties associated with all the factors which contribute to the inspection programme. For example, the maximum load in a member may vary from the predicted maximum load and the strength of a member is also subject to variation about a mean calculated strength. There is a finite possibility that the actual maximum load may exceed the actual strength of a component, as shown in Figure 5.3. Computation of likely distributions for all variables represents an impractically large computing problem. In practice, finite values would have to be assigned to each parameter and an assessment made mathematically of the likely range of real fracture criticality based on sample data (benchmarking).

When planning an inspection programme, the possibility of random defects should be handled by carrying out random inspections on non-critical components. This should be easy to accommodate in a real inspection programme; components with low overall inspection weighting would be selected on the basis of convenience to the location of the diving support vessel and the inspections already planned for components with high overall inspection weightings.

5.3.4 Criticality rating

For each inspection group, a ranking of components can be computed from the criticality rating of each component, ie the product of consequence of failure, Y, and likelihood of failure, X. An example spreadsheet layout capable of showing individual item weightings and the overall weightings for Y and X is presented in Figure 5.4.

Applying this inspection planning procedure to a new structure, there will be no in-service inspection history and the criticality rating will represent the overall inspection weighting. Application to existing structures requires that the ranking be compiled using up-to-date knowledge of the structure and therefore that the inspection history to date is incorporated.

5.3.5 Inspection history

The principal relevant inputs to ensure that historical information is accounted for in developing a rational inspection plan for an existing structure are:

- quality of records
- inspection history and findings
- when last inspected.

The quality of records and the inspection history will carry a fixed weighting through the life of the structure until such time as damage is identified. However, the date when a component was last inspected will change and the weighting to allow for this is the factor W introduced in Section 5.2.4 and Figure 5.2.

It is obvious that, for two components with otherwise equal weighting for inspection, it is preferable to examine in year n the component which was not inspected in year n – 1. Bearing in mind that the aim is to give the review panel a ranking of components for inspection in any year n (ie a ranking which changes from year to year), a simple additional weighting factor is required according to when the component was last inspected. As a first cut, an additive factor is proposed to ensure that components which have not been inspected recently appear relatively higher on the list for consideration in succeeding years, until they are inspected. Possible weightings would be:

Previous inspection	*Weighting*
• last year	add 0 to criticality rating
• 2 years ago	add 1280
• 3 years ago	add 2560
• 4 years ago	add 3840
• 5 years ago	add 5120
• more than 5 years ago	add 6400

The values of the weightings for W have been derived on the premise that the average component should be inspected every 5 years under normal circumstances. The 'average' scores for the weightings of likelihood of failure, X, and consequence of failure, Y, are both 80 (see Tables 5.1 and 5.2). The value of 1280 above is obtained from $(X_{ave} \times Y_{ave})/5 = 80^2/5 = 1280$.

5.3.6 A note of caution

The individual items making up the inspection weighting of a component and, more importantly, their numerical values in Tables 5.1 and 5.2 and in Section 5.3.5 require much more systematic review before they are adopted for planning the inspection of a real structure. The items and values shown in this report have been developed as a result of a limited research project which did not include any formal calibration or benchmarking studies.

5.4 CHOOSING INSPECTION METHODS

5.4.1 Relative costs and reliabilities of inspection methods

Before choosing an inspection method and technique for a specific component, the inspection planner must decide what quality of information is required. For example, if he knows that a through-thickness crack can be tolerated in a specific component he may opt to use flooded member detection (Section 7.2.6) with relatively low cost and high reliability rather than using high cost, low reliability magnetic particle inspection (Section 7.2.4). If complete loss of the component is not critical, visual inspection alone (Section 7.2.1) may be adequate.

The questions which should be asked in applying a specific inspection method to a specific component are:

- what quality of information is required?
- what is the cost of inspecting by this method?
- what is the reliability of the method and how is it affected by likely operational conditions?
- what is the cost of inspecting to give a satisfactory confidence level that the findings are accurate?
- is this cost commensurate with the overall inspection weighting of the component?
- what is the cost of repair/strengthening of the component (to reduce its inspection weighting)?

If the cost of repair is lower than the cost of identifying a defect before failure and the component is non-essential to overall integrity, it is self-evident that detailed inspection to identify the early stages of progressive damage is not cost effective. Provided that failure will be obvious to the eye, detailed NDE could be replaced by visual inspection.

Strengthening – in order to lower the inspection weighting of a component – should be considered where the cost of inspection is high, the reliability of inspection is likely to be low and/or the criticality rating of the member is high. Strengthening (preventative maintenance) is usually cheaper than repair.

If inspection reliability is known to be low, repeated inspection in a single inspection season should be considered, using different operators and techniques if possible. Because the cost of cleaning is usually a large proportion of total inspection costs, to clean once and inspect five times in a given year is likely to be more cost effective than cleaning five times and inspecting five times in successive years, although both give the same overall reliability. This procedure should only be considered for components with a low likelihood of failure, X, but a high consequence of failure, Y; otherwise there is a chance of missing the complete development cycle of a critical crack.

Although experimental work on crack growth in the past has concentrated on crack development prior to the crack going through thickness, this is slowly changing as fracture mechanics methods gain imputus from improved techniques and cheaper computing. This trend is of great interest to offshore operators, some of whom are already replacing magnetic particle inspection by cheaper and more reliable flooded member detection methods, although this approach means that there is no chance of discovering crack-like defects before they go through thickness. Nevertheless, an industry survey showed at least one operator considers that his overall chance of discovering an *important* defect is greater using flooded member detection since a far greater percentage of the overall structure can be covered for a given cost. This approach is particularly attractive for new structures, where crack-like defects are not anticipated. More detailed inspection of joints is appropriate where reanalysis or service history indicates high likelihood of premature cracking and inspection is still cheaper than repair.

5.4.2 Component category for inspection

Each component of a structure can be allocated a category for inspection purposes in accordance with the listing in Table 5.3. The category for a specific component is a function of its likelihood of failure, X, and the consequences of failure, Y (see Section 5.2.4). The category can be established automatically on the computer spreadsheet in Figure 5.4 where a column has been assigned to this purpose.

Appropriate inspection methods must be established for each of the four inspection categories. Examples of possible methods are given in Table 5.4. Desk and laboratory studies should be carried out for each method (as it is applied to selected typical components) to assess the cost of using the method to give suitable confidence that the actual inspection in practice will identify defects. The level of confidence required increases from category 1 to category 4; it is suggested that targets of 80%, 85%, 90% and 95% reliability be set for categories 1, 2, 3 and 4 respectively. This is independent of frequency of inspection and relates to reliability of inspection in a given season.

By multiplying the criticality rating of a component ($X \times Y$) by a cost weighting representing an appropriate inspection method for the component at a suitable level of confidence for its inspection category, a measure can be obtained of the probable cost of inspection of the component during the lifetime of the structure.

Characterisation of any defects is a separate topic; extra money would be justified in inspecting a single defect in considerable detail to allow sensible damage assessment (see Chapter 8).

5.5 INSPECTION PLANNING IN PRACTICE

5.5.1 Inspection in year 1

For a new structure, no weightings according to previous inspection history or when components were last inspected are required. The inspection ranking obtained by criticality ratings alone gives the nominal order of priority for inspection in each inspection group. In fact, practical considerations will modify the priority ranking. In the early years, high priority will be given to ensuring that:

- damage from installation activities is identified
- all appurtenances pertaining to fabrication, erection and installation are identified and recorded on as-installed drawings.

This represents a considerable volume of work and will almost certainly limit the amount of routine inspection as a consequence. On the other hand, damage relating to life in service (fatigue damage) should not yet be evident and the emphasis of inspection need only be on components with high criticality ratings. If it can be shown that components with high consequences and likelihood of failure can tolerate through-thickness cracking, flooded member detection (or some other technique which only identifies through-thickness cracking) seems an attractive inspection method. However, it should be used cautiously, since a crack which has developed so quickly to through thickness is almost certain to exhibit a short life to component failure. Detailed inspection of the most critical joints might be considered in preference to flooded member detection; the ideal would be to use both approaches.

5.5.2 Inspection in year 2

Planning for routine inspection in year 2 is based on the ranking from criticality ratings modified by the findings from year 1 and by the fact that inspection of some components took place in year 1. Firstly, all inspection weightings used in year 1 will be raised by 1280 in year 2 (see Section 5.3.5) except for those components that were inspected in year 1. Secondly, findings from the components inspected in the first year will be incorporated into the spreadsheet rankings by changing the relevant individual item weightings. For instance, a component showing unexpectedly high marine growth might be reassessed under item R (see Table 5.2).

As a result, different inspection priorities may be identified by the spreadsheet weightings, and the review panel will have to consider them.

5.5.3 Inspection in year N

In general, the rankings performed each year will identify the components requiring inspection, with rankings from 'essential' to 'desirable'. An operational review is necessary to determine possible execution plans to perform these inspections. A flowchart for this, which assumes the use of a support vessel for diving operations, is given in Figure 5.5. The result of this review will be an execution plan which ensures inspection of all components with a mandatory inspection requirement, which gives the widest possible coverage of other components with high rankings and which has capacity for contingency inspections (see Section 5.3.3).

Year by year inspection planning can proceed in this manner with inspection rankings changing in the light of the experience accumulated over the years. If and when minor defects start to be discovered, damage assessment comes in to use in a direct sense rather than in the optimisation studies of Section 5.2.5. The stages of this are:

- characterisation of the damage (by practical measurement and reference to historical data)
- analytical appraisal of the damage and its effect on the structure (damage assessment)
- decision on whether or not to repair immediately. The decision will be based on the expected time to component failure, the consequences of component failure and a comparison of the costs of continuing reliable inspection and of repair.

If the damage does not need immediate repair, the component's ranking will be reappraised. The weighting for defect known to exist (item N in Table 5.2) will increase to ensure that the component has high priority in the inspection ranking, even though the weightings for the confidence in assessments (items I and S in Tables 5.1 and 5.2 respectively) will have lower values.

Components or groups of components always appearing near the top of the priority rankings each year and yet always appearing undamaged during inspections can also be considered as candidates for assessment studies – to ensure that their rankings are, in fact, accurate. The weightings spreadsheet (Figure 5.4) will reveal which individual item is responsible for the high ranking and a change in its weighting may be justified. In this way, the ranking procedure itself is refined and tuned in the light of operational experience.

It must be emphasised that the ranking procedure is a tool for the inspection review panel, not a list of instructions. The actual steps in designing an inspection plan for a given year using this rational approach can be summarised as:

- compile the weightings and inspection ranking using the spreadsheet
- identify components that must be inspected (ie those with a high ranking)
- decide diving support vessel locations and timescales to allow those components to be inspected
- determine additional dive time that may be available
- select other components with high weighting that are conveniently located to the diving support vessel
- randomly select other components to inspect which do not have high criticality ratings but are convenient to the overall programme (see Section 5.3.3). Simple inspection techniques will be adequate for them (eg visual inspection or flooded member detection) unless unexpected damage is discovered.

5.6 WORKED EXAMPLE

5.6.1 History

To illustrate the effectiveness of this approach to the planning of underwater inspection, a worked example is shown on part of the first subsea horizontal framing panel of a steel jacket structure. This is an area of great inspection interest as it may well suffer both fatigue damage and impact damage from dropped objects or ship collision. Part of the frame is shown in Figure 5.6 but only the joints in the two areas indicated have been selected for ranking.

The structure was installed in 19N0. A general structural reanalysis was carried out in late 19N6 after MPI indications were discovered in joints 26 and 29. New inspection weightings were allocated to all components as a result. The reassessment involved detailed appraisal of critical joints at the legs (ie joints 1 and 2) and reappraisal of the conductor guide frames. The cracks were ground out and the reanalysis showed that there was no reason to expect premature failure. Poor quality fabrication was the likely cause of the defect in joint 31. The indication at joint 26 may have been erroneous as surface grinding and repeat MPI gave a clean bill of health.

Joints 1 and 2 were inspected in 19N7 and found to be free from damage. In 19N8, joints 37, 39, 47 and 48 were inspected; joints 47 and 48 were of particular interest as the reanalysis had indicated low fatigue lives (less than half the design life). Modelling in the reanalysis made conservative assumptions but inspection was carried out nonetheless, under the 'should inspect' criterion, ie not essential but desirable on the basis of questionable fatigue life. A crack indication was found in joint 47 late in the season.

5.6.2 End of inspection year 19N8

Figure 5.7 shows the spreadsheet of inspection weightings for the joints on completion of inspection in year 19N8. The 'last inspected' column has already been amended to give priorities for inspection the following year. Before looking at the overall weightings (the 'rank' column), it is worthwhile reviewing the individual weightings that have contributed to them.

Considering the individual items that make up the 'consequences of failure' weighting, Y:

- Item A is based on the subjective decision of an experienced designer and concerns the role of the component in the overall framework of the jacket.
- Because the *chord* member at each joint is primary, it is assumed that the loss of the chord as a result of joint failure would be serious at any of the joints. Item C therefore has a 'low' weighting (a high numerical value) throughout.
- The weighting for the redundancy of the brace member at each joint (item B) varies. Where the brace is secondary – in the conductor guide frame area – a medium weighting is appropriate.
- The likelihood of further short-term losses resulting from failure of each joint is given a weighting under item D.
- Items E, F and G are assessments of the possible consequences, other than structural, due to failure of the joint. For example, a failed riser support or conductor guide frame member increases the risk of lost production and environmental damage.
- Cost of repair (item H) is assessed subjectively. Much more detailed attention would be given to components which would be very expensive to inspect and which have a high likelihood of failure (see Section 5.2.5).
- Item I refers to the confidence in the assessment. A medium weighting implies a subjective assessment supported by representation in the structural model. A lower weighting (higher numerical value) implies that the component is not accurately represented in the structural model. When a detailed assessment of a particular component is undertaken (finite element analysis, redundancy analysis, etc) the confidence in the assessment increases and a higher weighting can be given. Joints 1 and 2 carry high weightings for item I because they were reassessed in 19N6.

The 'likelihood of failure' weighting, X, can be assessed more objectively on the first cut than the 'consequence of failure' weighting:

- Item M refers to susceptibility to accidental damage.
- If a defect is known to exist, Item N carries the very high weighting of 100. The fact should additionally be flagged in the 'inspection category' column of the spreadsheet. A damage assessment is almost certain to follow. If remedial action (eg crack grinding) is undertaken as a consequence, the weighting for item N will be reduced to 35. This is illustrated by joint 31 in the example – its inspection priority is higher than the almost identical joint 29.
- Items P and Q refer to the quality as well as the content of available data. Limited records will confer a higher weighting than well documented evidence.
- Item R is only given a non-average weighting if the marine growth is different from expectations. Normally, marine growth assumptions are incorporated into the design and these should be understood and taken into account by the inspection planner.
- The notes for item I in the list above are also relevant for item S here, the weighting for confidence in the assessment.

At the end of the 19N8 inspection season, the weightings for 'when last inspected', W, are increased to give next year's values.

The overall inspection weightings in Figure 5.7 are computed as $(Y \times X) + W$ (see Section 5.2.3) and are listed in descending order to give inspection priorities or rankings at the end of inspection year 19N8.

The method of fixing each component's 'inspection category' is defined in Section 5.4.2.

5.6.3 Subsequent action

The first action to be taken by the review panel is a closer examination of components shown by the 19N8 spreadsheet to justify further consideration. The ones at the top of the ranking are obvious candidates:

- Joints 31, 33 and 35 are adjacent on the platform (and can therefore be inspected as a group) and earlier damage in the similar joint 29 will not discourage the panel from inspecting these components in 19N9.
- Joints 47 and 48 (which were inspected during the 19N8 season) would be expensive to inspect regularly and the panel decide to undertake a detailed study of them to reassess their priority. The presence of the crack indication in joint 47 highlights a possible requirement for action before the winter. In this example it is assumed that

the reassessment is able to demonstrate that the small crack is stable under all loading conditions and will propagate only very slowly. It also demonstrates that joint 48 has a fatigue life in the medium category.

- Joint 26 is held near the top of the ranking because a defect is known to have existed. Its position alerts the review panel to the increased likelihood of further damage.
- Joints 3 and 4 are primary components (item A in the spreadsheet) and are due for inspection in 19N9 as a consequence of mandatory requirements.

It can easily be seen that the lowest inspection priorities are those with low consequence *and* low likelihood of failure (inspection category 1 in Table 5.3). In the middle of the spreadsheet are the joints in inspection categories 2 and 3, and decisions on which of these to inspect are a function of both required confidence and cost.

In the event, the review panel selects joints 47, 48, 31, 33, 35 and 4 for inspection in 19N9. When these inspections are actually carried out, the defect at joint 47 shows no discernable increase in size and is removed by light grinding. Joint 48 shows no defect and joints 31, 33 and 35 also receive clean bills of health. The area around joint 4 is seen to carry exceptional marine growth.

The effect of these changes on the inspection rankings at the end of 19N9 are shown in Figure 5.8. Appraisal studies in the winter following 19N9 might concentrate on the conductor guide frames; although no significant damage is materialising, the frame joints have high rankings. An assessment, which will allow reduction in the weighting due to item I if nothing else, would be worthwhile. If this were done before the next inspection season, the modified ranking would be used for planning inspections for the following year.

5.6.4 Lessons from the example

It is evident that the subjective individual item weightings suggested in this example have profound influence on the overall inspection rankings. To minimise this subjective influence, it is suggested that:

- all rules for the allocation of numerical values must be in writing, to ensure consistency of interpretation even when there are changes in review panel personnel
- data input should be centralised – a single microcomputer-based record with password access to a single user would be best
- the whole ranking method should be reviewed periodically to ensure that the weightings of individual items remain realistic
- it must be recognised that the ranking method is a tool, not a dictator.

A real structure would have a much larger number of joints than this example. Similar lists would also be developed for members, foundation condition and corrosion condition. It may well be that further simplification of the ranking method will be required but, whatever changes are made, the absolute weighting and ranking of a component are less important than its approximate position in the list. The ranking only points to components or groups of components which the review body should be reviewing.

Actual damage would, in practice, be dealt with in a much more systematic way than is apparent from this example. A rating of 100 for item N automatically highlights the existence of a defect. If, for example, the crack problem in joint 47 had not been solved by inspection of the crack and grinding, then its weighting would have stayed at 100 and the joint would still have been a special case for consideration, even if the review panel were confident of the crack's stability.

5.7 APPLICATION TO OTHER UNDERWATER INSTALLATIONS

Steel jacket structures are fairly tolerant of defects; even if errors are made in predicting the likelihood of component failure, there is not necessarily an important consequence before remedial action can be taken. Hence, the approach to inspection planning described above can be used cost effectively. On the other hand, pipelines, remote wellhead completions, templates and tethers have little or no redundancy, and the consequences of component failure are serious whether or not the likelihood of damage is high. Nevertheless, the techniques of damage assessment can still be applied to non-redundant underwater installations – hypothetically when the installation is undamaged or when it has one or more components damaged.

For an undamaged installation, the approach is to identify the fracture criticality (ie the criticality rating – see Section 5.3.4) of each component and then to assess the relative costs of inspecting or protecting the fracture critical components to give the required confidence levels. This methodology is simpler to apply than with platform installations as components are much less likely to suffer from widely fluctuating loads. On the other hand, almost all components are likely to be found to be fracture critical. Non-fracture critical components can be inspected on a component failure basis, eg by using visual inspection, flooded member detectors or load indicators (for tethers).

The relative costs of inspecting for damage and adding protection to minimise the risk of damage should also be taken into account. The cost of repairing a protected component must also be compared with the cost of repairing an unprotected component, in the event that failure still arises (from an unexpected cause). For example, a pipeline in a shipping lane may be buried to protect it from damage from fishing nets, anchor chains or dropped debris but a pin-hole leak in the pipe wall will be more expensive to repair as a consequence. Unfortunately, there is insufficient data available to make an objective assessment of these considerations for a given location and the judgement of the designer and the preferences of his client will prevail; a subjective assessment is inevitable. There have been recent efforts to protect subsea wellheads in the North Sea, but again the basis for the design of the protection is likely to be subjective. The problem is not dissimilar to that of ship impact on structures; there is a small risk of catastrophic damage but, the cost of protection against serious damage (particularly from impact) at some point becomes prohibitive. Techniques are available from risk evaluation specialists to handle this type of scenario.

For a damaged installation, the techniques for assessing damage (see Chapter 8) are unlikely to be used for damage that has been detected on fracture critical components. For over-riding safety and public confidence reasons, remedial action would always be taken. If a damaged component is not fracture critical, then failure tests might be preferable to detailed inspection (visual, flooded member detector, load indicator, etc).

For these low redundancy installations, it is concluded that damage assessment techniques are easier to apply than on jacket structures but are less likely to be of benefit. They can assist in the planning of inspection only by:

- identifying the fracture criticality of components
- deciding on the inspection frequency of fracture critical components where damage is likely to be progressive (see Chapter 8).

5.8 BENEFITS AND COSTS OF THE RATIONAL APPROACH

It is impossible to make an accurate commercial assessment of the cost effectiveness of adopting the proposed rational approach to inspection planning without carrying out a detailed, structure-specific study. This section gives an indication of how this study might be undertaken.

5.8.1 Benefits

By adopting the proposed approach, the operator of an installation would find himself with a model of his installation which provides the following:

- a basis for assessing inspection priorities which integrates the importance of fatigue and static damage considerations
- a rational basis on which to decide which components justify detailed studies
- a basis for assessing whether strengthening is cheaper than repair
- an indication of which inputs most influence the frequency with which a given component should be inspected.

This model is an important and versatile tool which the operator can use to assess his immediate and future inspection costs. Its power is further increased if it is integrated with a computerised inspection history database. Such databases are already under development by some operators. In addition, the operator will have established a team of experts (the review panel) to advise on all aspects of inspection and support the model with the necessary detailed studies.

The costs of establishing the approach are not cheap but the potential payback is considerable. As an example, assume that the model and studies show that the cost of stregthening a component to reduce its criticality rating is likely to cost the same as inspecting it twice in detail. Strengthening is therefore the cost effective option. It could be argued that this conclusion could have been reached from independent studies on single components perceived as expensive to inspect based purely on 'engineering judgement'. What would not have been possible, however, would have been an appraisal of the impact of specific reduced inspection requirements on *overall* inspection costs. Perhaps by removing, or dramatically reducing, the need to inspect a few key components, the operator could cancel two complete inspection seasons in every five, whilst still ensuring that his confidence in overall structural integrity is not diminished. The acceptability of this dramatic option could be tested by arbitarily altering parameters in the model prior to incurring the expense of detailed studies.

5.8.2 Costs and savings

It has not been possible to carry out a detailed cost-benefit analysis of this approach to planning inspection operations but, in adopting the approach, the operator is clearly faced with some costs, such as:

- hardware
- software development
- setting up the system
- detailed studies
- review panel
- ongoing system support costs.

These costs will only be justified if there is increased assurance of structural integrity, or reduced inspection costs without loss of integrity assurance.

The breakdown of costs in Table 5.5 is based on unsupported estimates of the costs of introducing the rational approach to a 200-member structure. The total cost of developing and running the system is seen to be of the order of £500,000.

The outcome of adopting the rational approach may be that five node inspections at depth can be saved each year. If diving costs are £30,000 per day (for saturation diving) and the inspection rate is one node per day, total annual savings may be:

• offshore costs, 5 × £30,000	£150,000
• inspection planning, allow 2 engineers × 4 weeks	£10,000
• reporting costs	£10,000
• total saving, per annum	£170,000

It is immediately apparent that there is potential for a significant return on the high initial cost of adopting the new approach to inspection planning (particularly if the zero inspection option can be used in, say, one year in five). The additional benefit is that a consistent approach to decision making is used throughout the lifetime of the structure. It is not practicable to assess the impact that this will have on increased safety assurance, but in any event, the system will be at least as safe as it is with current methods of inspection planning.

5.9 INCORPORATION OF PROBABILISTIC METHODS

The deterministic method described in this Chapter is a practical method for global evaluation of inspection priorities, but certain aspects of the allocation of points may be refined if the randomness and uncertainties in the input physical parameters are recognised. Because of the complexity of the probabilistic approach it may not be possible to evaluate inspection priorities for the whole structure but there will often be benefit in assessing the critical structural components in depth using probabilistic techniques.

A brief technical introduction to probabilistic concepts is given in Appendix 2.

5.9.1 The probabilistic approach and its advantages

The probabilistic approach associates a mean value, a standard deviation and a probability density function (or distribution) with each input parameter. Thus the derived or output variables also have associated with them a probability that they deviate from the mean – given by their standard deviation and probability density. The deterministic analysis roughly corresponds to the same procedure, but with the mean value taken as the actual value. The conclusions of a deterministic analysis are recoverable from a corresponding probabilistic analysis by assuming a standard deviation of zero (zero spread), which assumes a probability of one or certainty that the input and output parameters have a value equal to the mean.

Considering by way of illustration the depth of a crack in a tubular joint determined by probabilistic fracture mechanics[5.2], then the probability that the crack depth varies from the expected or mean value is also available. It is then possible to determine the probability that the crack will have penetrated through-thickness and hence that 'failure has occurred'. As the influence of uncertainty in the input parameters such as material properties and loading history are explicitly represented in the analysis it is also possible to quantify the effect of these uncertainties on the result. In this way the critical input parameters may be identified and resources channelled into those areas where maximum benefit would be gained by an improvement of knowledge.

Madsen[5.2] considered a single K-joint typical of an offshore platform using both the S–N curve-based fatigue and the probabilistic fracture mechanics approaches. He concluded that the relative importances shown in Table 5.6 should be attached to the various uncertainties involved in his example.

One very important area of uncertainty not mentioned in the above is the probability of detection of a crack or defect (a subject under active investigation at University College, London). This uncertainty may be represented by the assumption that a defect of undetectable size is always present and by assuming that a particular probability distribution is associated with initial crack lengths – the idea being that a larger crack has a larger probability of detection and hence has a lower probability of being present but remaining undetected. In this way the probable crack length may be rationally modified in the light of the results of an inspection.

This process is illustrated in Figure 5.9, a figure which must be used with caution as actual numerical values are not represented to scale:

- The upper part of the figure shows a postulated undetectable defect of mean depth a_{di} with its associated spread of depth shown by the distribution curve plotted against a vertical axis. As time passes (T increasing) the expected crack depth increases as shown by the solid line and its spread of depth also expands due to uncertainties in parameters such as loading history and local material properties. Just before inspection there is a small but finite probability P_f that the crack has achieved the critical crack depth a_c. If, as indicated, an inspection indicates that no crack is present then the expected crack size may be set back to a_{di} with a distribution that reflects the probability of detection of a crack of mean depth a_{di}. As time progresses the uncertainty in the crack size increases again as does the expected crack depth. Also shown on this figure are the 80% confidence limits which indicate the range of crack depths which have a probability of occurrence of 80%.
- The lower diagram shows a similar situation but now a crack has been detected. This results in a change of the expected (or mean) crack depth with a smaller range. As time progresses up to repair there is a small probability of failure, indicated by P_f. After repair the crack depth returns to that for an undetectable crack of a_{di} (a different value may be appropriate depending on the repair method). As before, loading uncertainties extend the range of probable crack depths for subsequent times.

In summary the probabilistic technique offers the following advantages over the deterministic approach:

- the probability of detection of a crack may be incorporated into the analysis as uncertainty in the crack depth
- critical input parameters may be identified as priorities for further investigation
- the results of an inspection may rationally be incorporated into the analysis
- the effect of small changes in input parameter values may be quantified without further calculation as distributions about expected values of the output variables are available.

5.9.2 Application of probabilistic techniques in inspection planning

The deterministic approach described in Section 5.2 allocates a weighting to the various influencing terms in the likelihood of failure of a structural component. In the probabilistic approach a direct measure of the probability of failure P_f of a component is calculated together with measures of the confidence in the assessment from the spread in the output variables. This probability of failure may be directly compared with the acceptable probability of failure P_{faccep} by the ratio:

$$Z_j = P_f / P_{faccep}$$

A value of Z_j near to 1 would indicate that inspection of the component is necessary. The inspection history of the component is directly incorporated into the probability of failure in that (expected) crack depths are automatically modified in the light of the inspection; no artificial modifier to Z_j is necessary to take account of inspection history.

Figure 5.10 illustrates the probabilistic approach.

This approach shares an important difficulty with the deterministic approach, namely how to determine the acceptable probability of failure or consequences of failure part of the equation. Naturally, as in the deterministic approach, a number of influencing terms need to be taken into account. These are the same as those discussed in Section 5.3 with the exception of the confidence in the assessment terms (items I and S in Tables 5.1 and 5.2 respectively) which should result automatically from the probabilistic analysis. In particular, further work is required to examine the redundancy of a structure to relate the acceptable probability of failure of a component to the (acceptable!) probability of failure of the whole structure. A value of 10^{-4} for the acceptable probability of failure of a component before the first inspection has been quoted in Reference 5.2. This corresponds to a reliability index value of 3.72. The acceptable probability of failure of the whole structure would be less than 10^{-4} reflecting the degree of redundancy of the structure with respect to failure of this component. As failure of a given component would result in a re-distribution of load which makes failure of other components more or less likely, an evaluation of the structure's overall reliability is difficult to quantify. It may not of course be necessary to quantify the overall reliability in arriving at a reasonable value for P_{faccep}.

5.9.3 Extension of the probabilistic method

Although only failure caused by fatigue crack growth has been considered above, in principle it is also possible to predict brittle fracture of a structural component at any stage in fatigue crack growth. If this check is made during a fracture mechanics calculation then the probability of failure resulting from this cause may also be included in the overall probability of failure term.

Consideration of the trajectories of dropped objects may also yield probabilities of damage due to this cause giving a further contribution to P_f.

The potential of the probabilistic approach is apparent. The complexity of the method need not be an insurmountable problem if the proper computer hardware and software can be assembled to make the approach manageable in size and comprehensible to the pragmatic end-user.

Table 5.1: *Suggested weightings for individual items affecting the consequences of failure, Y, of one specified joint*

Consequence of failure, Y_j, of joint j = $A_j + B_j + \ldots\ldots + I_j$ where:

Symbol	Influencing item	Weighting value		
		High	Medium	Low
A_j	Primary (high), secondary (medium) or tertiary (low) component	40	10	1
B_j	Redundancy of brace	1	10	40
C_j	Redundancy of chord	1	10	40
D_j	Likelihood of other short-term losses	20	5	1
E_j	Immediate risk to life	100	10	1
F_j	Immediate risk to environment	100	10	1
G_j	Immediate risk of lost production	50	10	1
H_j	Cost of repair	20	5	1
I_j	Confidence in assessment	2	10	40
Y_i	(Medium rating)		80	

Table 5.2: *Suggested weightings for individual items affecting the likelihood of failure, X, of one specified joint*

Liklihood of failure, X_j, of joint j = $K_j + M_j + \ldots\ldots + S_j$ where:

Symbol	Influencing item	Weighting value		
		High	Medium	Low
K_j	Fatigue category	40	10	1
M_j	Susceptibility to damage	20	5	1
N_j	Defect known to exist*	100	35	5
O_j	Corrosion condition at last inspection	20	5	1
P_j	Material	20	5	1
Q_j	Fabrication quality	20	5	1
R_j	Excessive marine growth	10	5	1
S_j	Confidence in assessment	2	10	20
X_i	(Medium rating)		80	

* *Damage assessment studies required in addition to reclassification to high weighting*

Table 5.3: *Categories of components for inspection purposes*

Category	Consequence of failure weighting, Y	Likelihood of failure weighting, X
1	Low	Low
2	Low	High
3	High	Low
4	High	High

Table 5.4: *Possible inspection methods for different inspection categories*

Inspection method/technique	Inspection category (see Table 5.3)							
	Joint				Member			
	1	2	3	4	1	2	3	4
Visual Inspection by ROV	•				•	•	•	
Close visual inspection by diver	•	•				•	•	•
Single MPI(1)		•	•	•				
Multiple MPI(2)			•	•				
Flooded member detection	•	•			•	•		

1. *Clean and inspect once*
2. *Clean and inspect three or more times with different divers and modified procedures*

Table 5.5: *Preliminary estimates of costs of introducing the rational approach to inspection planning*

Area	Description	Cost (£)
Hardware and software development	Hardware and software development Obtain or program a 'cost of reliable inspection' model	10,000 100,000
Setting up the system	Subdivide the structure Design proformas Learning curve Preliminary ranking (for 200-member structure) Obtain compound weightings Postulate initial detailed studies Allow 1 senior engineer and 1 junior engineer for 6 months	32,000
Setting up and review panel	Review initial recommendations Allow 4 consultants for 6 days	6,000
Setting up and detailed studies	Define studies Appoint and monitor contractor Allow 1 senior engineer for 2 months	7,000
Detailed studies	5 initial detailed assessments	125,000
Setting up and review panel	Reassess priorities and define further studies	10,000
Detailed studies	10 further detailed studies	200,000
Setting up and review panel	Reassess priorities and define inspection priorities	20,000
Total		510,000

Only those costs additional to conventional inspection planning have been included

Ongoing system support costs for this approach are expected to be of a similar magnitude to those for conventional inspection planning

Table 5.6 *Sources of uncertainty*

Approach	Source of uncertainty	Importance
S–N based fatigue	Environmental description	1%
	Load model	19%
	Stress analysis	13%
	Fatigue strength (S–N curve)	60%
	Damage criterion	7%
Fracture mechanics	Environmental description	1%
	Load model	19%
	Stress analysis	20%
	Stress intensity factor	10%
	Material crack growth parameters	50%

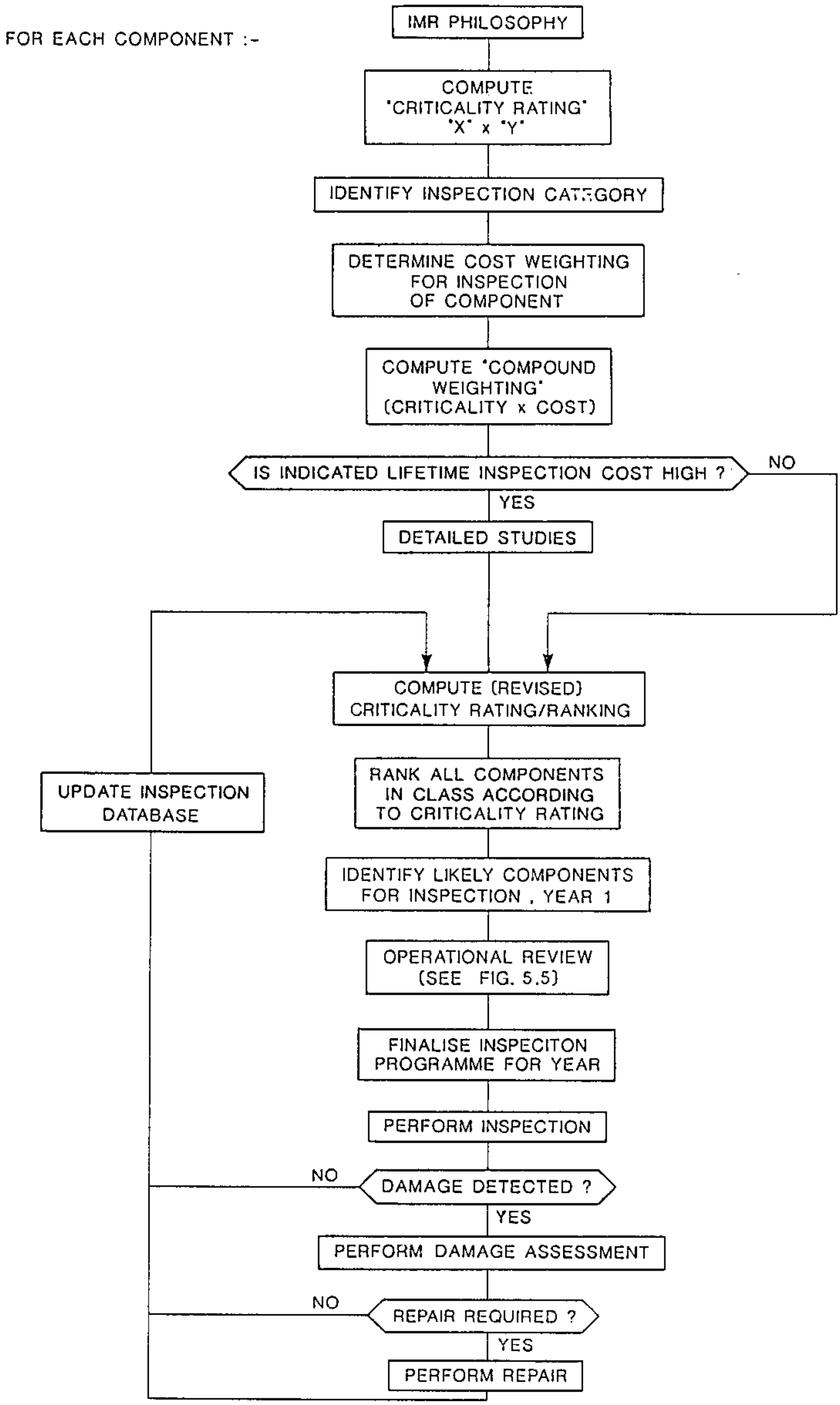


Figure 5.1: *A rational approach to planning the annual inspection programme*

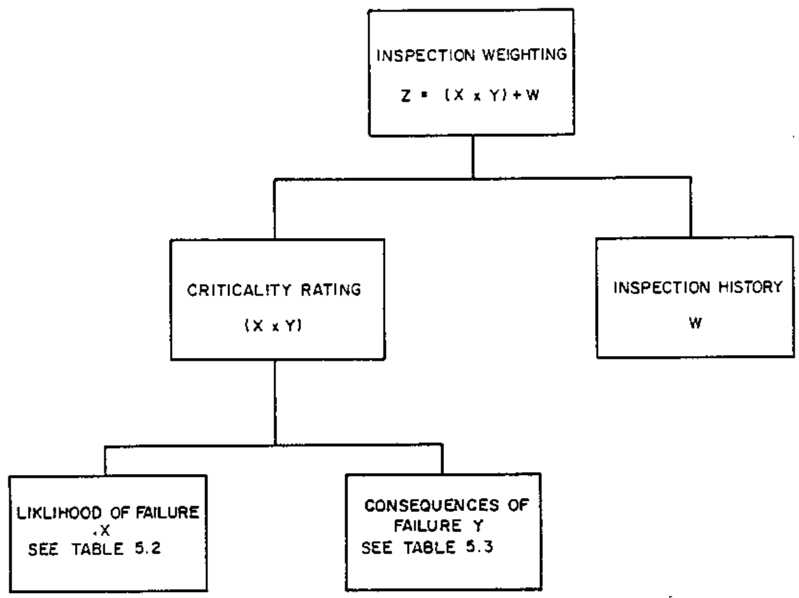


Figure 5.2: *Computation of overall inspection weighting, Z*

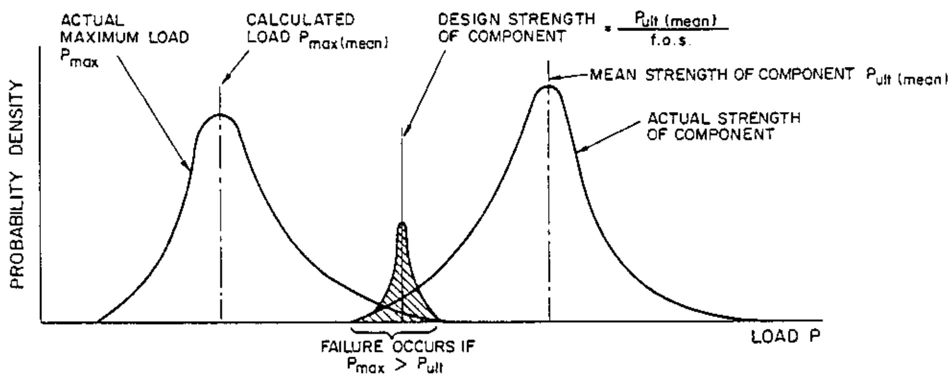


Figure 5.3: *Relationships between load-carrying capacity and load in a component*

JOINTS - END OF INSPECTION YEAR 19N9

JOINT	DESIGN	REFERENCE DRAWING	ACCESS (1-5)	LAST INSPECTED W	CONSEQUENCE OF FAILURE										LIKELIHOOD OF FAILURE									RANK (Y) x (X) + W	INSPECTION CATEGORY	NOMINAL PRIORITY
					A	B	C	D	E	F	G	H	I	Y	K	M	N	O	P	Q	R	S	X			

Figure 5.4: *Example of spreadsheet layout showing inputs to overall inspection weightings of joints*

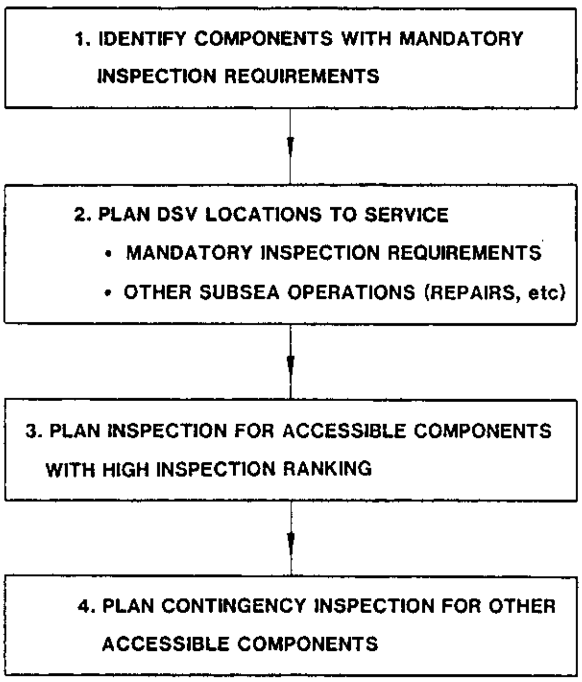
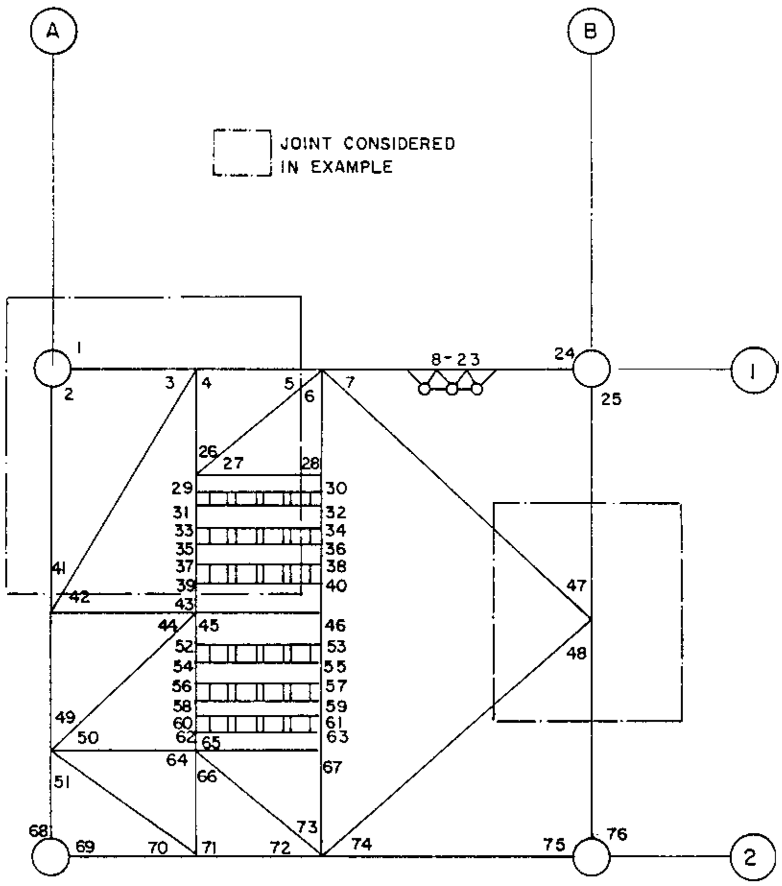


Figure 5.5: *Flowchart for operational review of components requiring inspection*



CONDUCTOR GUIDE FRAME AT EL (-) 38'-0"

Figure 5.6: *Worked example – part of the first subsea horizontal framing panel on a steel jacket*

JOINTS - END OF INSPECTION YEAR 19N8

JOINT	DESIGN	REFERENCE DRAWING	ACCESS (1-5)	LAST INSPECTED W	CONSEQUENCE OF FAILURE A	B	C	D	E	F	G	H	I	Y	LIKELIHOOD OF FAILURE K	M	N	O	P	Q	R	S	X	RANK (Y) x (X) + W	INSPECTION CATEGORY	NOMINAL PRIORITY
47	-38	Sketch 1	1	1280	40	40	40	20	10	1	1	5	10	159	40	20	100	5	5	5	1	10	178	29582	4	1
31	-38	Sketch 1	4	3840	10	10	40	20	1	10	10	5	40	146	10	5	35	5	5	20	10	20	110	19900	2	2
33	-38	Sketch 1	4	7680	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	18776	2	3
35	-38	Sketch 1	4	7680	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	18776	2	4
48	-38	Sketch 1	1	1280	40	40	40	20	10	1	1	5	10	159	40	20	5	1	5	1	1	10	91	15749	4	5
26	-38	Sketch 1	2	3840	40	40	40	1	10	1	1	5	10	148	10	5	35	1	5	5	5	10	76	15088	2	6
3	-38	Sketch 1	1	7680	40	40	40	5	10	1	1	5	10	152	1	20	5	1	5	1	5	10	48	14976	3	7
4	-38	Sketch 1	1	7680	40	40	40	5	10	1	1	5	10	152	1	20	5	1	5	1	5	10	48	14976	3	8
29	-38	Sketch 1	4	3840	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	14936	2	9
1	-38	Sketch 1	1	2560	40	40	40	20	100	1	50	20	2	313	1	20	5	1	1	1	5	2	36	13776	3	10
2	-38	Sketch 1	1	2560	40	40	40	20	100	1	50	20	2	313	1	20	5	1	1	1	5	2	36	13776	3	11
37	-38	Sketch 1	4	1280	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	12376	2	12
39	-38	Sketch 1	4	1280	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	12376	2	13
27	-38	Sketch 1	2	3840	10	10	40	1	10	1	1	5	10	88	10	5	5	1	5	5	10	10	51	8328	1	14

Figure 5.7: *Spreadsheet showing the ranking of joints at end of inspection year 19N8*

JOINTS - END OF INSPECTION YEAR 19N9

JOINT	DESIGN	REFERENCE DRAWING	ACCESS (1-5)	LAST INSPECTED W	CONSEQUENCE OF FAILURE										LIKELIHOOD OF FAILURE									RANK (Y) x (X) + W	INSPECTION CATEGORY	NOMINAL PRIORITY
					A	B	C	D	E	F	G	H	I	Y	K	M	N	O	P	Q	R	S	X			
31	-38	Sketch 1	4	1280	10	10	40	20	1	10	10	5	40	146	10	5	35	5	5	20	10	20	110	17340	2	1
47	-38	Sketch 1	1	1280	40	40	40	20	10	1	1	5	2	151	40	20	35	5	5	5	1	2	105	17135	4	2
26	-38	Sketch 1	2	5120	40	40	40	1	10	1	1	5	10	148	10	5	35	1	5	5	5	10	76	16368	2	3
29	-38	Sketch 1	4	5120	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	16216	2	4
3	-38	Sketch 1	1	7680	40	40	40	5	10	1	1	5	10	152	1	20	5	1	5	1	10	10	53	15736	3	5
1	-38	Sketch 1	1	3840	40	40	40	20	100	1	50	20	2	313	1	20	5	1	1	1	5	2	36	15108	3	6
2	-38	Sketch 1	1	3840	40	40	40	20	100	1	50	20	2	313	1	20	5	1	1	1	5	2	36	15108	3	7
37	-38	Sketch 1	4	2560	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	13656	2	8
39	-38	Sketch 1	4	2560	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	13656	2	9
33	-38	Sketch 1	4	1280	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	12376	2	10
35	-38	Sketch 1	4	1280	10	10	40	20	1	10	10	5	40	146	10	5	5	1	5	20	10	20	76	12376	2	11
4	-38	Sketch 1	1	1280	40	40	40	5	10	1	1	5	10	152	1	20	5	1	5	1	10	10	53	9336	3	12
27	-38	Sketch 1	2	5120	10	10	40	1	10	1	1	5	10	88	10	5	5	1	5	5	10	10	51	9608	1	13
48	-38	Sketch 1	1	1280	40	40	40	20	10	1	1	5	2	151	10	20	5	1	5	1	1	2	45	8075	3	14

Figure 5.8: *Spreadsheet showing the ranking of joints at end of inspection year 19N9*

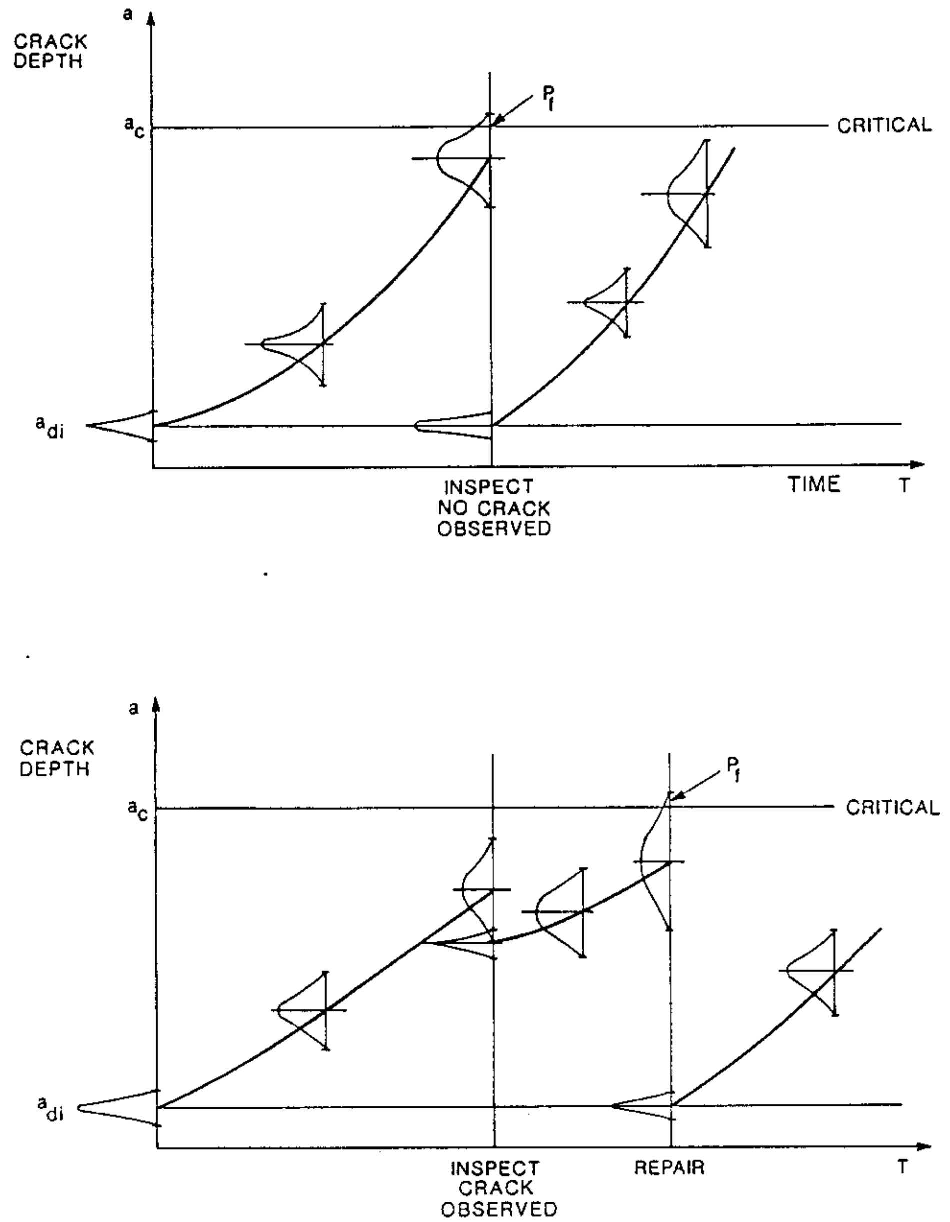


Figure 5.9: *Crack growth and inspection*

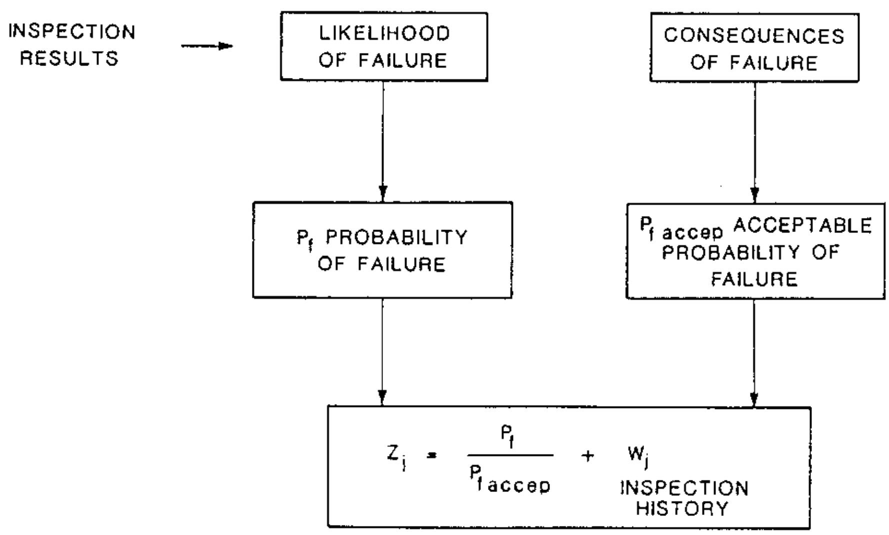


Figure 5.10: *Overall determination of inspection weighting – probabilistic method*

6 Management of inspection operations

6.1 INTRODUCTION

Underwater inspection is a multi-disciplinary and complex process which depends on attention to detail and preparation for its effectiveness. A fully defined inspection system and an effective management structure are therefore essential.

This chapter outlines a management system which should enable the performance of inspection operations to match the sophistication of approach to inspection planning described in Chapter 5. It will assist organisations, particularly operating oil companies, to develop an appropriate management structure to ensure effective and cost-effective implementation of their inspection philosophies.

There is great disparity between the inspection systems (and the inspection terminology) used by different operators but this chapter describes a generalised coherent system and provides a framework in which recommendations can be made; there is no intention to portray the definitive system. The recommendations here are based on the assumption that inspection is to be conducted within an 'anomaly-based' system, one which should benefit from the application of computer techniques.

Each operator also has its own management structure and where reference is made here to operators' management groups they are intended to be areas of specialisation rather than sections, departments or divisions of an oil company.

6.1.1 Definitions of terms used in this chapter

(Words printed in italics are defined elsewhere in the list.)

Activity
A defined item of inspection (or repair) work. Its specification and procedure should be defined for each *task*.

Anomaly
An occurrence of a *property* exceeding its *threshold* as defined for a particular *task*.

Anomaly-based system
An *IRM* system based on the concept that subsequent actions, eg *response activities*, are selected following consideration of discovered *anomalies* and their *properties*.

Barrel
Main component of a *node*.

Component
A recognisable part of a primary or secondary structure.

Construction Project Group (CPG)
Centre of expertise within an oil company responsible for design of a structure, fabrication quality assurance and installation. It is assumed that the *CPG* is disbanded following handover of the installation (complete with its design and yard data) to the operating oil company.

Inspection co-ordinator
A qualified inspection specialist usually provided by the diving contractor or an inspection house, who manages the inspection and data-collection processes offshore.

Inspection data
The immediate result of an inspection *task*, consisting of readings, measurements, descriptions and sketches of *anomalies*.

Inspection Management Group (IMG)
Centre of expertise within an operating oil company where inspection legislation is interpreted, inspection philosophies are developed, communication is conducted with certifying authorities, 5-year inspection schedules (in the UK) are designed, and *inspection data* collection and processing is supervised.

IRM
Inspection, repair and maintenance.

Job Pack
A collection of information and pro forma, both technical and operational, for the offshore inspection team providing all references and materials for recording *inspection data*.

Marine Operations Group (MOG)
Centre of expertise within an operating oil company where responsibility lies for the economic execution of underwater inspection, selection of contractors, contract management, safety audits, offshore safety and logistical considerations and budget management.

Node
A point on a welded steel structure where two or more members meet. It consists of a *barrel* as the main body with one or more *stubs* to which other members are welded.

Operator's Engineering Group (OEG)
Centre of expertise within an operating oil company where all theoretical studies are undertaken and responsibility lies to consider consequences of failure, acceptable levels of damage, component criticality and inspection priority ranking. Studies may include redundancy, refined fatigue analysis, fracture mechanics, dented member studies, preventative maintenance (strengthening) and repairs.

Operator's Offshore Representative (OOR)
Offshore personnel to whom the Operator's Contract Representative delegates some responsibilities for conduct of a contract.

Property
A value, condition or attribute (eg corrosion or cracking) of a *component* that is to be the subject of measurement or examination during inspection. For each *task*, a *property* would have defined *thresholds* beyond which it is considered to be an *anomaly.*

Response activity
An *activity* ordered by an *Operator's Offshore Representative* following crossing of a *threshold*, ie discovery of an *anomaly.*

Response Guidelines
A tabular presentation of successive *thresholds* and *response activities* to guide the *Operator's Offshore Representative* should he need to decide on appropriate responses to *anomalies.*

Review Panel
A forum within an operating oil company of specialists in structural design, quality assurance, inspection and diving set up by management to provide an overview of the *IRM* process and ensure co-ordination. See Section 5.2.3.

Scope of Work
A detailed presentation of work to be performed.

Structural inventory
A list of all *components* of a structure, with appropriate references.

Stub
A short section of tubular steel joined to a leg or member at a *node*. It takes up the curvature of the *barrel* so that a bracing member may be butt-welded to the *stub.*

Task
A set of *activities* to be performed on a *component.*

Task List
Proforma for the listing of *activities* to be performed on specified *components*, together with comments and references.

Threshold
A defined value or condition of a *property* which, when exceeded, calls for a decision to be made by the *Operator's Offshore Representative.* He may order *activities* to be performed, as defined and presented in the current issue of the *Response Guidelines.*

User specification
A study of an organisation's needs, prior to the design of a computerised inspection system.

6.1.2 Management structure

The operator's management groups – CPG, IMG, MOG and OEG – are defined in Section 6.1.1 above. In addition, the Review Panel, recommended and described in Chapter 5, should be formed at the early stages of a project to co-ordinate dialogue between the management groups, whose roles are highly inter-dependent.

Due to the high cost and potentially disruptive nature of underwater operations, strategic decisions are made by relatively senior management following advice from the groups and the Review Panel. On a day-to-day basis less senior personnel are necessarily required to take decisions on points of detail, factors which nevertheless have considerable ergonomic and economic consequences. The management structure should therefore ensure selection of personnel with adequate communication skills and the ability to undertake responsibility and make decisions. Everyone involved should also have no doubt as to where responsibility lies.

Obviously, the groups involved in the generalised inspection system described in this chapter cannot correspond to all operators' sections, departments, etc. It is a vital task, therefore, for the managers concerned to examine their resources in the light of the inspection system adopted and ensure that the delegation of responsibility, the power to influence and the necessary expertise are all coincidental.

Inspection can only be effective if there is continuity in the methods used. No system can cope with such complex processes if its basic elements are periodically ignored or its methods amended piecemeal. The gradual development of a complete system and in-house expertise should be the concern of management.

6.2 THE INSPECTION SYSTEM

An approach to inspection planning is recommended and described in Chapter 5. Implementation of the plan is a complex interactive process that needs to be conducted within a system. Although it would not be possible for all operators to adopt the same inspection system, or even agree on such basic concepts as 'close inspection' or 'defect', the generalised inspection system described here introduces the essential elements of a system capable of matching the sophistication of inspection planning already recommended.

6.2.1 Principles of the anomaly-based system

(Words marked with an asterisk in this section and Section 6.2.2 are defined in Section 6.1.1.)

In an anomaly-based inspection system*, activities* (eg cleaning, debris removal and inspection) are performed to find and quantify defects. In order that data is not obscured by unqualified personnel with arbitrary definitions of defectiveness, the system uses the concepts of property* and anomaly*. A property is a value, condition or attribute of a component that is to be measured or examined during its inspection. For example, the property corrosion may vary from mill scale to total disintegration.

A property is said to be anomalous only when it is measured or found to be beyond defined limits. The limits are known as thresholds*. For example:

- the threshold limits for the property cathodic potential may be from 'more positive than –800 mV' to 'more negative than –1150 mV'
- the threshold for the property crack may be 'any', since the discovery of any crack may require response activities* to be performed
- the threshold for the property wall thickness may be 'greater or less than 10% of expected'
- the threshold for the property specification inconsistency may be 'any' (an ROV survey logging incorrect identification marker plates or undocumented appurtenances would treat these findings in the same way as it would debris or abrasion).

Discovery of an anomaly calls for appropriate response activities* to be performed.

The Offshore team is issued with a Job Pack* which includes definitions of properties, their threshold limits and recommendations for response activities. It also includes a set of activity specifications which specify the resolutions and methods for the activities that are to be performed. Thus onshore personnel are assured that all properties beyond limits defined by qualified specialists will be reported and that anomalies will receive appropriate attention.

6.2.2 Overview of the system

Once an inspection programme has been planned (see Chapter 5), the Operator's Engineering Group* (OEG) and Inspection Management Group* (IMG) need to generate a Scope of Work*, often utilising service companies at this stage. They should agree:

- a list of tasks* to be performed
- the specifications and procedures for the activities to be performed on each component*
- the property definition and threshold limit for each property
- the Response Guidelines that delegate and guide the Operator's Offshore Representative* (OOR) on which activities he can order in response to anomalies.

The IMG is then able to produce data sheets for each task and can collect the documents mentioned above into a Job Pack for issue to the offshore team. Alternatively, the selected diving contractor may produce this work in the form of a Field Specification. Either way, following award of a contract, close liaison is established and schedules can be agreed.

Offshore, the divers' observations are prompted by the inspection co-ordinator – usually provided by the diving contractor or an inspection house. He manages the inspection and data-recording process. The Job Pack should enable him to be self sufficient, but is likely to require certain decisions to be made by the OOR.

Execution of the tasks is governed by priority and by logistical restraints (eg water depth, weather, sea currents, vessel movements, deployment locations). As inspection progresses, the OOR reacts to any discovered anomalies according to his Response Guidelines. When the gravity or implications of an anomaly exceeds his guidelines, onshore members of the IMG or OEG should be involved. Either way, response activities will be applied.

The report containing the inspection data collected offshore may be produced by the inspection contractor or the operator, and may be compiled manually or electronically. Ultimately it will be processed by the IMG and analysed by the OEG. The objectives of the analysis are:

- to assess the validity of the data
- to identify components with anomalies requiring further actions
- to define those actions and modify the schedule accordingly
- to identify recordings that can be disregarded as anomalies
- to recommend modifications to activity definitions, property definitions and threshold limits for future Scopes of Work, and agree them with IMG
- to assess the overall integrity of the structure and detect trends which may require action at a later date
- to recommend any special studies required.

IMG personnel should provide input to these assessments and also assist the Marine Operations Group (MOG) process and analyse operational data. Operational analysis produces recommendations for modifications to the activity definitions, and possibly to the choice of methods envisaged for future work.

When these analyses are finished, a cycle of inspection has been completed.

6.2.3 Structural inventory

The structural inventory is an essential part of any inspection system. It determines how the installation is divided into the parts that receive direct attention and provides for cross referencing with:

- design data (see Section 6.3.3)
- fabrication yard data (see Section 6.3.4)
- underwater inspection data (see Section 6.3.5)
- operational data (see Section 6.3.6).

It is usually practical to organise component identification as a progressive sub-division of components: a jacket, sub-divided into frames (or levels), sub-divided into nodes and members, sub-divided into welds, tubulars, plates and attachments such as anodes and supports. (However, some companies do not identify nodes as components but allocate items at each node to its member.) Supports are sub-divided into welds, plates, inserts, bolts, continuity straps, and so forth. In this way reference to a member would include its anodes, access manholes and circumferential welds without having these necessarily listed or itemised on inspection drawings (although they could be).

Information to be included for each component depends on the intended capability of the inventory system. Cross-references and data that commonly are included are:

- component identification used during underwater inspection
- component identification used during design
- component identification used during fabrication
- top and bottom water depths
- component type (eg member or weld)
- governing dimensions (eg external diameter and length)
- identification of the larger component of which it forms a part (eg 'Frame C')
- component identification of adjacent components
- as-installed-drawing reference
- pre-float out photographic references
- inspection drawing reference for global inspection
- underwater access orientation
- location of underwater identification marker plate (if any)
- special characteristics (eg flooded, coated).

Compilation of an inventory is time consuming. It must be decided at the outset what is to be considered as an identified (ie numbered) component and what is to be considered as part of a component (but can be seen on an inspection drawing or found fairly easily amongst the fabrication data). Parts commonly in the component list include:

- nodes
- members
- riser sections (ie sections between framing levels)
- caisson sections (ie sections between framing levels)
- J-tubes sections (ie sections between framing levels)
- supports (to risers, caissons and J-tubes)
- anodes
- reference electrodes (if any)
- piles
- pile guides and sleeves
- node barrel-to-stub welds
- single-sided closure welds
- other components with high criticality ratings (see Section 5.2.4)
- access manholes
- conductor frames
- conductor sections (ie sections between levels)
- seabed (area grids beneath and around the jacket).

Component numbering needs careful consideration at the outset. Should it prove necessary to revise numbering at a later stage, considerable confusion will result. Although grouping the components into types is necessary for the allocation of inspection specifications and is useful for planning schedules and estimating factors and for searches, incorporation of grouping codes into component numbering can lead to inflexibility. Incorporation of three-dimensional co-ordinates can assist divers and ROV pilots to orientate themselves quickly. Evident logic in any numbering system tends to assist detection of errors. Identifications that are too long cannot be seen to be correct or wrong at a glance, particularly by data recorders who may not understand the elements of the identification. Care should be taken to give identifications visual impact and to avoid obvious confusions (eg letter 'S' with the number '5', 'I' with 'L' or '1', the letter 'O' with the number '0', etc).

6.2.4 Inspection drawings

Offshore inspection data collection requires inspection drawings to be laid out and referenced to suit the operating conditions of the dive control cabin. All information has to be quickly available and clear to personnel unfamiliar with the installation and working possibly in conditions of poor light.

There are three kinds of inspection drawings:

- *Global drawings* where the structure is divided into drawings suitable for eyeball ROV inspection. Each drawing may show a frame, part of a frame or a level, with all components of interest shown and identified. It is also useful if each component can be referred to on one global drawing, which is quoted in the structural inventory.
- *Local drawings* to be used when close or detailed inspection is undertaken. These consist of a drawing of the component concerned, usually accompanied by a location

sketch. They should communicate necessary information (ie show appurtenances, underwater identification marker plates, nuts, earthing straps, etc), be accurately drawn (although dimensions are usually omitted) and of sufficient size to allow marking up of cathodic potential reading points, wall thickness measurement reading points, camera orientation angles and any anomalies (eg abrasions, dents and debris).

- *Special drawings* for presentation of data. These include isometrics and whole parts of a structure, with data clearly presented for communication of processed results.

Production of these drawings lends itself well to computer-aided draughting because the same drawings are re-used over the years but marked up or presented differently for various purposes. CAD is particularly effective for concrete inspection drawings where anomalies are usually represented in the form of dimensioned sketches. CAD drawings of whole concrete components can be marked up with numbered anomalies, the details of which can be accessed by cursor and zoom facility. Another benefit is that searched categories can be displayed on global views of the structure.

The creation and storage of a three-dimensional model of a whole structure offers benefits too, particularly for the presentation of defects and to aid orientation. However, not only the cost of such a development, but the implications of its use should be given careful consideration. There is great merit in using a conventional system where the same plans and elevations are used time and time again (for dimensioning and also for comparison). Orthodox views are also more easily stored and retrieved. Inspection personnel should not be too hasty to discard standard engineering drawing practice which has developed over the years for good reason.

6.2.5 Inspection specification

Activity specification

An activity has been defined here as an item of inspection work. Activity specifications define the governing parameters of the activities when:

- techniques and resolutions are being selected during task design
- a pre-qualification inquiry is circulated
- estimating is being carried out
- tenders are invited
- Job Packs and Task Lists are compiled
- data is being analysed.

Activity specifications should have at least twelve elements:

- *Description* – enables the activity to be recognised and differentiated from others (eg 'ultrasonic compression wave probe wall thickness and lamination testing').
- *Resolution and accuracy* – determines the limits within which an anomaly may be detected. They should therefore be compatible with the threshold limits that determine when a property is and is not considered an anomaly (eg 'resolution: 1 mm depth, 0.1 mm normal full screen deflection').
- *Operator qualification* – also has a direct bearing on the validity of the data (eg 'CSWIP 3.2U' or 'CSWIP 3.ID + 10 hours experience').
- *Equipment* – listed to aid the contractor, but also to prompt the OOR to check whether or not the contractor is fully equipped for the activity (eg 'A-scan display equipment, compression probes, calibration blocks, measuring rule, tape, wire brush and scraper).
- *Consumables* – treated in the same way as equipment (eg 'paintsticks').
- *Facilities required* – to assure the contractor that the necessary facilities will be available. It also serves as a prompt for those concerned to ensure that the facilities are made available (eg 'unit battery recharging point/power supply').
- *Standards* – references to any British Standard codes of practice or established guidelines according to which the activity is to be performed (eg 'BS 4331 : Methods used in assessing the performance characteristics of ultrasonic flaw-detection equipment').
- *Preconditions* – the activities that should have been completed beforehand (eg 'verification of location and clean to remove all foreign materials such as marine growth, deposits, accretions and protective coatings').
- *Job Pack requirements* – the information that needs to be prepared for the activities (eg 'location, preconditions, extent, marking-out increments').

- *Recording requirements* – exactly what data is to be recorded (eg 'verification of calibration readings').
- *Estimating factors* – suggested durations of in-water preparation time and activity performance time (eg 'air diving – preparation 30 min, performance 4 h/m^2; saturation diving – preparation 45 min, performance 4 h/m^2; ROV – N/A').
- *Code* – to refer uniquely to the activity as defined in the specification. There may be others for the same technique, but with different resolutions.

Activity procedures

Activity procedures are normally provided by a diving or ROV contractor and accepted by the operator's IMG. The procedures must comply with the requirements of the activity specification and must state all actions necessary to perform the activity. The IMG should provide the expertise, either in house or contracted, to accept or modify the procedures; unquestioning reliance on contractors' procedures has sometimes been the cause of inconsistent data recording.

By way of example, the headings of an activity procedure for 'magnetic particle inspection' are:

- equipment specification (dimensions, weight, depth ratings, power supply)
- ink specifications
- ink preparation
- equipment preparation
- inspection surface preparation
- methods of magnetisation
- inspection techniques
- demagnetisation
- remnance test.

Properties and threshold limits

Ultimately, defects are of interest to personnel of the OEG, who decide what defects are significant. The concepts of property and threshold limit are strictly communication devices to ensure accurate handling of data on defects. Threshold limits are not usually values at which failure occurs. They may be the design assumption; they are the point at which the property is anomalous and where response activities are normally ordered.

With the property 'anode defects' for example, the threshold may be 'upon discovery of quiescence', 'defective attachment' or 'abnormal wastage'. The 'abnormal wastage' threshold is itself not fixed. Since the design assumption for the rate of anode wastage may be 'less than 5% per year', the limit for wastage set in year 10 would be 50%. Similarly, the absence of an anode defect in year 5 implies there was no anode wastage greater than 25% and the absence of anode defect in year 15 implies there was no anode wastage greater than 75%.

A set of property definitions and thresholds should form part of the Job Pack for a contract. To some extent the set is constrained by the resolution of the inspection activities; categorisations should reflect not only what is of interest to members of the OEG, but also what can be differentiated offshore. The set of properties used successfully by one operator is:

Property	*Descriptions*	*Code*
Anode defects	abnormal wastage, absence	AD
Burial	of member, guide frame or pipe	BU
Coating defects	in paintcoat or neoprene wrap	CD
Cracking	any crack, confirmed or suspected	CK
Cathodic potential	in negative mV	CP
Corrosion	general or local pitting (not toe defects)	CR
Debris	any debris, eg metal, rope, paintspills	DB
Deposits	corrosion products	DP
Global damage	deflected, buckled, parted or impacted member	GD
Grinding (remedial)	pre- and post-installation	GR
Local damage	dent, abrasion, gouge, flame-cut, arc-strike, penetration	LD
Marine growth	hard and soft	MG
Relative movement	between components	MV
Scouring	abnormally low seabed level	SC

Settlement	of the installation or field	ST
Specification inconsistency	any mis-match between actual and documentation or drawings, or installation errors (eg of underwater markers)	SI
Toe defects	undercut, crevice or preferential	TD
Wall thickness		WT

As with other codings of an inspection system, the codings for properties should be fixed at the outset, since late changes cause considerable problems (see Section 6.2.3). However, the system should allow frequent changes in thresholds; these are intended as the means of communication between OEG, IMG, the contractor's inspection co-ordinator and the diver in order that clear conclusions can be drawn about properties addressed during particular inspections.

6.2.6 Job Pack

Task List

For effective underwater inspection, information needs to be collected by the IMG and presented clearly for rapid and easy access by contractor's personnel offshore in the dive or ROV control cabin. In the generalised system being described here, the document forming the link between the IMG and contractor's personnel is the Task List. It is included in the Job Pack, attached to the three documents described in Section 6.2.5 above.

In the Task List, all tasks (the set of activities to be performed on a component) of the scope of work are listed together with necessary references and instructions. Items to be referenced for each task are:

- task number
- installation
- year
- means of intervention (eg ROV or air diving)
- component identification
- top and bottom water depth
- activities to be performed
- property thresholds for each activity
- activity specification reference for each activity (see Section 6.2.5)
- activity procedure reference for each activity (see Section 6.2.5)
- reference of document that called for the task to be performed
- special notes (eg area of possible ship impact)
- data sheet numbers where task data is to be recorded.

It is recommended that the task numbers are short and simple. They should not incorporate indications of more than:

- the year
- the installation
- a number.

The need for task numbers for use during analytical searches diminishes the more computer techniques are implemented. For manual data handling it is necessary for each task number to be unique and give access to a grouping of all the items referenced to it on the Task List.

Data sheet pro forma

Data sheets, on which inspection data is first recorded, should be designed to prompt and accommodate all inspection findings. They are sometimes known as component sheets. Their clarity and completeness have a direct bearing on the 'value' of the data collected. Ambiguous prompts and fields and any need to improvise data entries to accommodate the unforeseen renders data unsuitable for rigorous processing. It should always be borne in mind that the data will be processed, analysed and used by people who were not offshore at the time of the inspection. They will only be aware of any circumstances and concerns that affected data collection offshore if they were clearly documented at the time.

The data includes all aspects that reflect on the resolution of the technique in use, and references to link the data with what preceded it (via the Task List) and what succeeded it (the response data sheets). Data sheet pro formas should enable recording of:

- data sheet number
- installation
- date
- means of intervention
- inspection drawing or drawing reference
- task number or component number
- activities requested
- inspection qualifications of the diver (if appropriate)
- equipment used
- calibration data
- video and photographic references
- results (eg cathodic potential readings, requested dimensions of anodes, cracks or indentations, areas and thicknesses of marine growth, verbal descriptions)
- acknowledged (ie answered) prompts for a predetermined list of properties as to whether each exceeds its predetermined threshold
- reference to enable direct access to response activities and results arising from each property
- inspection drawings (see Section 6.2.4) where data can be marked up (eg sketched anomalies, camera angles, CP contact reading points)
- initials of inspector (or OOR).

Where many standard, ready-made pro formas have been used to record the results of all the combinations of activities per task, manual sorting offshore and final report production onshore runs the risk of becoming a suffocating exercise. An over-complex manual paper system offshore may be responsible for delays and damaging shortcuts and may divert attention away from the actual inspection process. Computerised on-line data collection pro formas could be beneficial in these circumstances. The screen could prompt and format itself in response to what is encountered; sorting and report production could follow automatically. However, attempts to date at on-line computerisation have suffered from slow operation, particularly where graphics are involved.

Data sheet designs should be the subject of continuous revision and refinement, but always within the constraints of the original fundamental concepts. This is to avoid the fixed design of data sheet pro formas (and task sheets and number systems) imposing a legacy of grey areas, inefficient operation and confused referencing, as has unfortunately occurred in the past.

Response Guidelines

It is normal to delegate power to the OOR to initiate response activities to some anomalies as they are encountered offshore. He should have enough experience to know what responses are appropriate in some cases or he may have direct access to IMG or OEG personnel who would advise him. However, for smooth efficient management, he should be in a position to initiate a series of previously agreed response activities without consultation. He should also know when he has come to the limit of his delegation. In addition, personnel analysing data from a completed inspection should know not only the responses ordered by the OOR but why he ordered them. If a series of guideline responses are drafted and agreed, one for each property and its threshold, then these requirements would be fulfilled.

Figure 6.1 is an example of guidelines for the property 'CK:Crack'. Properties are shown by two-letter codes as explained in Section 6.2.5 and response activities by three letter codes, such as RDG for 'refer to datum for general inspection' or CL3 for 'clean to Swedish SA $2^1/_2$–3 standard'. The guideline consists of a sheet with four columns (from left to right):

- *Property* – is CK since the sheet in this example applies to cracks only.
- *Threshold*, the first threshold value is 'any' since the brief is for responses to be ordered if any crack is discovered. The threshold 'crack confirmed by close visual inspection' determines whether or not to proceed with detailed inspection.
- *Response activities* – are listed in the order they are to be performed in response to a particular threshold being crossed.
- *Properties of particular interest* – are provided as prompts to direct attention when the response activities are being performed.

The sheet is followed line by line down the page until a threshold is not crossed. At that point, work ceases.

Response Guidelines of this sort should bring about continuity and serve as a means to communicate the operator's IRM philosophy to contractors' personnel. As a further refinement, offshore representatives could be required to write a report justifying any deviation from the guidelines. The guidelines should be as flexible as possible, and revised to reflect specific concerns of IMG and OEG. Issues of the guidelines should be referenced and stored, as data forming part of the histories of components.

Familiarisation Information

It is important that contractors' personnel learn the geometry of the structure being inspected as early as possible. For safety's sake everyone concerned should know the locations of features such as suction caissons, artemis beacon stations and dangerous debris. To facilitate this and to aid communications generally, the OOR, diving supervisor, inspection co-ordinator, ROV pilot and ship's master should all be issued with drawings marked up with work locations and areas of concern for safety. Isometric drawings, sometimes exploded and with risers and caissons colour coded, have been successfully used for this purpose.

It has also been found that the interest and involvement of inspection personnel can be encouraged if they are given a pack of information about the installation and its context. They appreciate knowledge of its purpose, history and vital statistics rather than dealing only with just another collection of nodes, risers and supports or with anonymous acres of concrete surface. Views from the pre-float-out photographic survey always generate interest.

6.2.7 Offshore operations

Section 7.4 later outlines the different intervention methods available for underwater inspection operations, although it is outside the scope of this book to give all the information necessary to enable selection of the most appropriate method of intervention for a given inspection task. The choice of method – air diving, mixed gas diving, ADS, ROV, etc – and whether the operator owns or hires the necessary plant and equipment are dictated by many factors, including:

- number of installations and volume of work
- inspection techniques to be applied
- water depths
- expectation of weather
- deck and bed space available
- operator's or contractor's in-house preferences (eg platform or vessel deployment, mini-bells or surface decompression)
- state of the market.

Control of offshore operations is delegated to personnel from any one of the four centres of expertise defined in Section 6.1.1 – CPG, IMG, MOG or OEG – with others providing supporting services. Ultimately, many decisions are made by non-specialists on the advice of specialists. Operators need two-fold representation offshore:

- an inspection specialist from IMG, capable of verifying correct inspection practice
- a diving or ROV specialist from MOG, sufficiently experienced in safety, certification and underwater operational practice to verify safe practice and compliance with the contract on behalf of the Offshore Installation Manager and to play the necessary role during an emergency or other incident.

Whether or not both roles can be fulfilled by one person depends on the qualifications of any individuals involved.

6.3 DATA MANAGEMENT

The three corner-stone requirements of an inspection data management system are that it should:

- provide certainty for decisions to be made, based on sufficient and correct information (accessible collections of data form the links between the specialist groups that collaborate to undertake the inspection cycle)

- operate with sufficient speed
- be flexible enough to cope with changes in organisation, methods, legislation and the state of the installation.

Section 5.2.4 in the 'Planning' chapter of this book describes how the inspection priority of a component is a function of the consequences of failure, the mode of failure, the likelihood of failure, the cost and reliability of inspection, the inspection history to date and certification requirements. Considering the number of components on even a small jacket platform and the volume of documentation involved, it can be seen that the task of data management to provide such a perspective is very large, and potentially expensive in itself. The volume of data generated during the design, fabrication, installation and operation of a jacket is enormous, involving drawings, documentation, video-cassettes and photographs, between them occupying many metres of shelf-space.

Operators have learned that they cannot afford simply to leave inspection systems to evolve; data not properly handled is effectively lost and data not consistently defined can rarely be incorporated into a body of knowledge. Rather than allow the accumulation of effectively useless data, it is essential to create a system that will encompass all data relevant to inspection and integrity appraisal before a structure is installed. Nevertheless it would be a mistake to start from nothing and immediately install a costly, sophisticated and elaborate computerised system. Experience has taught that an organisation should develop its system in stages to ensure it is compatible with its methods of operation and in-house experience. All stages of system development would benefit from continuous scrutiny by the Review Panel introduced earlier in Section 5.2.3.

This section considers how such a system inter-relates the sets of data: from design, fabrication yard, underwater inspection and operations. They are related to each other, and to the structural inventory, to produce the variety of reports that enable user groups to function.

6.3.1 User specification

Inspection systems are expensive to set up and it is therefore vital to produce a comprehensive user specification to ensure that system sophistication and the amount of data handling is no more, but no less, than that necessary to serve the needs of the users. Since the specification dictates the amount and timing of documentary transfer from a construction project group (CPG), an early and important action is to appoint a team to produce the specification. It should address each phase of the inspection cycle and its inter-relationship with data originating from design, fabrication, installation and underwater inspection. The team should create a model representing the flow of information, identifying the input sources, the output reports and particularly the decision points. At each point, the following questions should be answered:

- who is responsible?
- what does he need to know in order to function?
- how quickly does he need the information?
- how often does he need the information?

The team that produces the user specification should have experience in computer data-base information systems, but should above all be able to question users persistently – until all the requirements of the system are defined.

6.3.2 System sophistication

It is a management decision as to when resources should be expended in development of an inspection data-management system, how sophisticated it should be and at what stage it should be developed. Sophistication varies from totally manual to fully computerised data-base with facilities for real-time offshore operation and expert/knowledge-based systems.

Currently available data-base and spreadsheet packages enable masses of data to be accessed and manipulated rapidly and to a level impossible by manual methods. Manual methods often prove expensive to set up and run and there is a limit to the size of clerical tasks that can be performed without an accumulation of errors (because adequate checking for errors is usually impossible). A hybrid solution between the manual and the data-base methods consists of a suite of simple computer programs to file and manipulate data on disk (and it may be possible to transfer the data electronically into a full data-base at a later date). Search facilities can ensure elementary cross checking and error traps can detect some input errors, but the programs for hybrid methods can consume many man hours of effort; they often grow beyond a size appropriate to their sophistication. And, when transfer to a full database is proposed, electronic data transfer is notoriously hazardous.

In practice, manual and hybrid methods are often used for a trial period prior to full computerisation, to perfect the system before it is made permanent in expensive software. If this path is followed it must be realised that some results eventually to be produced by computer will take many man hours to produce manually and some of the operation speeds dictated by the user specification (see Section 6.3.1 above) may need to be relaxed during the period of manual operation. Such trial periods are only fully worthwhile if the user specification has been completed and accepted, the underlying concepts have been fully thought through and numbering systems have been designed in detail. Furthermore, some inspection drawings will have to have been produced and a workable access procedure devised for design and fabrication data. These steps require an appreciation of the eventual sophistication of the system so that substantial clerical and draughting tasks do not have to be repeated.

6.3.3 Design data

Structural design data is usually handed over to the operator in documentary form and computer models are created from parameters extracted from the data. Design parameters, and results of analysis of the models (eg to consider the effects of changes in deck loading or mud accumulation over horizontal members) need to be accessed by OEG and the Review Panel to formulate their inspection strategy and tactics, as well as to assess and respond to inspection results.

If criticality rating of components is used for inspection planning (see Section 5.2.4) there must be a way to combine component weightings derived from design (ie the likelihood of failure and the consequences of failure) with weightings dependent on fabrication and inspection history (including time elapsed since the component was last inspected). This could be done manually; design data could stand in isolation, for incorporation with inspection history once every certification period (5 years in the UK). However, the ranking method of Chapter 5 would be more effective if design data were tied into the structural inventory, the inspection data and operational data, to enable a larger collection of data to be manipulated by OEG for optimum solutions. This would require considerable preparation work, especially as design data is not normally presented in a manner compatible with inspection, or even fabrication, data. A feasibility exercise and cost analysis should determine whether the improved perspective and saving in later analysis time would justify the exercise.

6.3.4 Fabrication yard data

Data

At various stages during and immediately after fabrication, volumes of quality-assurance documentation, as-built and as-installed drawings and lists of 'relaxations from specification' are handed over to the operator, but usually presented in a form incompatible with underwater inspection. As with design data, a feasibility and cost analysis exercise should indicate to what extent this data could usefully be extracted and tied into the components listed in the structural inventory. For instance, the following data could be extracted and transferred to the inspection data base:

For weld components

- component identification used during underwater inspection
- as-built drawing number
- archive references (ie how more information can be retrieved manually)
- weld procedure reference
- NDT applied
- period of NDT
- NDT report reference
- recorded anomalies (if any)
- number of repair areas (if any)
- preparation procedure reference (if any)

For tubular components

- component identification used during underwater inspection
- as-built drawing number
- archive reference
- can/tubular identification
- steel type
- outside diameter
- wall thickness
- mill reference identification
- plate identification
- cast number.

Self-evidently this is an expensive exercise. Many clerical errors may occur and the checking exercise alone is onerous. However, it may be the only way that yard data will ever be exploited in practice to rationalise later underwater inspection from the points of view of both effectiveness and cost.

Photographic records

It is strongly recommended that extensive pre-float-out photographic surveys are made of jacket structures and their secondary components. Yard photographs prove invaluable for communication, to explain appurtenances and to verify correct location under water. They considerably reduce the learning curves of all personnel concerned with inspection and encourage interest and involvement. However, the results are only useful if:

- Underwater identifications are used. This presupposes that design of the complete component numbering system is well underway before fabrication is complete.
- The underwater orientation of each photograph is known. It is necessary to use a coding for camera orientations for this purpose. If the lens centre-line angle at the time of exposure is noted in the form of codes relative to the horizontal (eg straight up, 45° up, level, 45° down, straight down) and, say, the shore line (left, 45° left, parallel, 45° right, right) then the codes can be transcribed by a simple computer program to their underwater orientations to give, for example, 'Node N-13D3 – from the south east, looking down'.
- Photographs are presented in the report orientated as they appear on the upright immersed structure. This can be achieved if what will be vertical on the immersed structure is photographed parallel to one side of the print. Each photograph can then be fixed onto a page with that edge up-and-down. This is of great importance, since it significantly increases the recognition speed of the report user.

6.3.5 Underwater inspection data

Because the management of data from underwater inspections cannot be considered in isolation from the constraints of the offshore situation and because the over-riding concepts of an inspection data system, manual or computerised, are very difficult to alter once the system is in operation, it is imperative that the requirements of a data management method are not beyond the ergonomic constraints of offshore data collection. To avoid this, experienced inspection personnel at all levels should be consulted before and during the development of the method. If their concerns are overlooked for the sake of intellectual elegance or short cuts in computer programming – as has all too frequently happened in the past – the results inevitably are: wasted in-water time, inconsistency in the recording of data, wasted opportunity to record 'clean' data, large accumulations of effectively useless data and poor deductions from the data.

The two main priorities once inspection is under way are that spread time (and in particular divers' bottom time) is utilised fully and that the complete inspection, recording and storage system can establish the status of the components inspected to the satisfaction of people onshore. The system determines how a diver or ROV inspects, how his findings are expressed and what work the inspection co-ordinator and OOR are required to do during inspection, between tasks and between dives. The system thus affects the productivity of the team. It also determines what can be deduced from the data. A balance must be struck between the ideal and the practical; if the data recording requirement approaches being ponderous, there is a temptation to seek informal short cuts. This inevitably brings into question the validity of the whole inspection system despite the accuracy with which the data is later processed and presented.

For the generalised system being described here, six items of data are relevant for each underwater inspection task:

- task number
- component identification
- activity performed (ie their specifications and procedures)
- property threshold limits applied
- anomalies encountered
- task number of response actions.

Some apparently trivial decisions concerning data recording can have profound operational consequences. To insist on making a physical note of all null entries during an eyeball ROV inspection (ie all observations where a property does not exceed its threshold) would call for thousands of entries and it may even be over-onerous during close inspection by a diver. On the other hand, unless it is certain which property has been addressed during which activity, at what resolution and at which threshold limits, data processing may lead to incorrect deductions. The conclusion may be, for instance, that there was no corrosion before a particular date when in fact there was corrosion but beyond the resolution of the technique applied or the underwater inspectors had not addressed corrosion at the time. Specific null returns against specific defined properties reveal more from the inspection. Rather than the oft-repeated phrase '...appears to be in good condition with no visible defects...', the data should reveal: 'no metallic debris', 'no hard marine growth thicker than 75 mm', 'no anode more than 25% depleted', etc. Data of this standard can be achieved if the ergonomics of the dive/ROV control room are considered in data sheet design and if prompting procedures are introduced.

Similar attention needs to be applied to component numbering. Computers can only search for numbered components but there is no point in noting, for instance, when an ROV passes over a circumferential weld on a member if it is concealed within marine growth and three may be passed in five seconds.

The application of computers offshore to record inspection data requires careful consideration. They may produce prompting data sheets (screen or paper) with automatic input of such items as equipment used, property thresholds, activity specification references and video time. This should reduce paper handling but, unless the keyboard operation and screen design aspects are totally compatible with offshore ergonomics, much expensive underwater time could be wasted. The use of computers also requires keyboard skills and familiarisation with the software. This introduces another constraint in contractor personnel selection and affects the learning process offshore. It also requires more equipment to be mobilised and maintained and more faults to be rectified. Section 6.4 later discusses in more detail the use of computers in underwater inspection.

6.3.6 Operational data

Underwater work, including inspection, merits financial analysis to ensure productivity, foresee over-spend and assist accurate estimating. However, estimating for underwater work is not easy because of variable downtime and unforeseen tasks, and cost control is not easy because of the rapid turnover of work offshore and the many other demands on offshore personnel.

Operational monitoring is usually based on noting start times of activities against coded events in a log. The logging is usually done (as an additional duty) by the inspection co-ordinator, OOR or diving supervisor. Sometimes it is done by trainees or even students. Time available for the logging is not only limited but greatly variable and pressure of the operational events themselves may result in it being missed altogether. The more codes to be logged, the more onerous the task becomes and when there are too many codes, accurate data collection becomes impossible. As with inspection data, the ergonomics of the logging should be considered before a method is adopted.

Operational events should be logged separately from contractual events. For instance, minor malfunctions could be logged for better understanding of equipment performance, but contractual 'breakdown' may only be applicable to major events. Similarly, operational problems caused by sea conditions, such as 'sorting out tether', should be analysed without confusion with contractual 'waiting on weather'.

The list of coded operational events should coincide as far as possible with events that are normally recorded in logs. For instance diving supervisors and ROV pilots always note 'diver leaves bell' or 'ROV out of cage', 'diver on location' or 'ROV returns to cage'. Thus transit periods should conveniently start and end at these points. Similarly, the OOR always records contractual events such as 'standby' and 'breakdown' and the completion of tasks and of the activities within tasks. Masters also record vessel movements. The operational logging exercise could become a systematic means of exploiting standard practice.

Operational events may be allocated to groups so that, if there is no time to log individual events, there should still be time to log the groups. Events within the groups can also be rearranged to suit the people involved, providing the groups themselves remain constant. For instance, some work can clearly be seen to be in the group 'in-water performance of activity' rather than 'in-water preparation for activity'. Other groups could be 'in-water support work', 'surface support wirk', 'decompression' and 'waiting on'. Thus all on-shift time can be allocated to one group or another. The number of operational events within a group can be varied. For instance, the group 'in-water support' could contain up to about fifteen events, eg 'diver in transit', 'diver secures downline', 'diver awaits work basket', 'diver untangling tether', etc.

The creation of too many events and codes poses its own problems. For example, a diver may leave the bell, go to location, inspect, leave location for the basket, change tools, return to location, inspect and return to the bell. Which of these trips is 'in-water preparation' and which 'in-water support'? If a round trip to the basket is considered to be in the group 'in-water preparation', is it allocated to the inspection activity before, or the one after, or is it pro-rated between the two? If the distinction is not clear, the recorder may produce biased results. In practice, recorders who become confused tend to log too many events and then find themselves overburdened.

The operational events logged should correspond with those used in estimating. An estimate for a full scope of work could then be presented as a computer spreadsheet with measured times and prices for some activities of each task, other times and prices provided by default if necessary and unknowns pro-rated automatically on assumptions input by the estimator.

For contract cost control offshore, if groups, task numbers, activity codes and financial codes are input, the same spreadsheet could compare actual performance with completed tasks in order to identify unforeseen productivity, conduct the daily cost control and automatically draft the daily telex of percentage of tasks completed, percentage of budget committed, list of tasks completed, duration of main events, etc. Simple programs could also search for and list uncompleted tasks in a specified area and depth or the outstanding tasks involving a particular activity, eg close-up photography. If performance was found to differ from that estimated, revised assumptions could be input into the spreadsheet to predict the amount of over-spend.

Onshore, the analysis would be more thorough, with an exact match of estimate with actual. Its main uses would be:

- to improve estimating factors
- to improve the algorithms used
- to justify choice of equipment and methods
- to illustrate improved performance following innovation.

6.4 COMPUTERISATION

The repetitive nature of underwater inspection and the multiplicity of components involved would suggest that more extensive use of computer techniques should considerably improve inspection and assessment ability and yield substantial cost savings.

It is not possible here to give detailed guidance on the computerisation of inspection systems since the market changes so rapidly. What can be done is present a summary of pros and cons for computerisation, offer the results of an informal survey and suggest a development approach. The aim of all these is to disseminate some of the lessons learned by the North Sea operators who have ventured some way down the path of computerisation.

Computerisation of inspection systems is an area of rapid development and considered to be of high priority by most operators.

6.4.1 Why use computers in inspection information work?

Below is presented a summary of pros and cons for computerisation, abstracted and developed from the various references to computers throughout this chapter:

Pros	*Cons*
• Standardisation of reporting formats throughout an operating company.	• Service companies have to use different reporting formats for each operating company.
• Fast retrieval of data for additional inspection information.	• Difficult to restrict the flow of information.
• Fast production of presentations from varied types of information	• With enough data it is possible to represent information in a misleading manner.
• Fast analysis of results	
• Fast production of final reports	
• All work can be carried out on site offshore. It may thus require fewer man hours for report production and should eliminate drafting errors.	• Change of work practices for service companies. Report production offshore is more expensive per hour.
• Reduction in offshore clerical work.	• Need to select another category of contract personnel.
• Reduction in onshore clerical work.	• Contracted personnel may require more time for acquaintance with the system.
• Small amount of floor space stores large amounts of information.	• More cabin space and beds necessary offshore for computer operators.
• Data is quality controlled as it is being collected.	• More equipment malfunctions to be rectified.
• Inspection data cannot be altered after it has been accepted.	• Errors are less obvious in processed data.
• Reduction in time to prepare the work programme.	
• System is dependent on organisation needs instead of on individual preferences.	• More difficult to develop methods that benefit from individual operatives' experience.
• Only collects information required and reduces time spent in gathering redundant information.	• Shortcomings in the system may lead to the collection of vast amounts of redundant information.
• Work can be re-planned during the inspection programme.	• Possibility of diving team waiting on keyboard operations.

6.4.2 Experience from computer systems currently in use

An informal survey in 1987 involving nine North Sea operating oil companies revealed:

- 2 operated purely manual inspection systems.
- 3 operated advanced computer systems.
- 4 operated semi-computerised 'hybrid' systems.
- 4 had not considered it economic to produce their inspection drawings by CAD.
- 2 had effectively achieved a graphics/data mix, although several had received reports from inspection houses containing this mix.
- 5 used inspection systems that were anomaly based, and the others recognised it is as the way to go.
- All had experience of individual functions that do not interact as well as could be achieved, eg data with graphics, task list with data sheet production.
- All had an ongoing development programme for computer systems which will cover many years, and had learned that the final solutions offered by service companies are illusionary.
- Some had experienced problems where a system had been developed to fit around one person's ideas.

- 2 admitted that over-reliance on a single service company's software and personnel had led to over-dependence on that company.
- Some felt they could use inspection data better by not restricting it to individual departments or geographical locations. Shortcomings had arisen from poor co-ordination between departments, the problems being managerial rather than technical.
- Some felt that the data collected could prove useful to departments such as Accounts, Planning and Central Records.
- Some felt that other, more basic, information should be integrated with the inspection data, eg:
  - physical measurements(eg water depths)
  - criticality ratings
  - as-built drawings
  - specifications and procedures.
- Some admitted that mistakes had been made and repeated:
  - hardware that was difficult to upgrade had to continue to be used
  - systems had required specialist operators
  - systems were too specialised and inflexible.
- Some admitted that short-term solutions had been applied to long-term problems.
- Some had developed inspection computer systems incompatible to their corporate computing philosophy.

6.4.3 A proposed development approach

It is recommended that the following points are considered by companies about to embark on computerisation of an underwater inspection system:

- Maintain an overview of the computerisation developments by the Review Panel (see Section 5.2.3). Software development is not purely a computing concern; during the short period of time of the development, concepts and methods are in effect crystallised. The need for free and effective communication is of the utmost importance.
- Select a small potential list of likely developers.
- Set a test for all developers.
- Ensure the user specification is complete and acceptable to all parties (see Section 6.3.1).
- Let the chosen department or company analyse the user specification to produce a functional specification.
- During the above phase, use a prototype to demonstrate the designed system before the major work takes place.
- Ensure that the computerised system is compatible with the corporate computing philosophy. Involve a representative from the computer department.
- Develop a system with as many off-the-shelf software packages as possible and practicable.
- Maintain tight project control QA/QC procedures during system development.
- Be wary of proposed changes to the inspection system arising from computer considerations (see particularly Section 6.3.5).

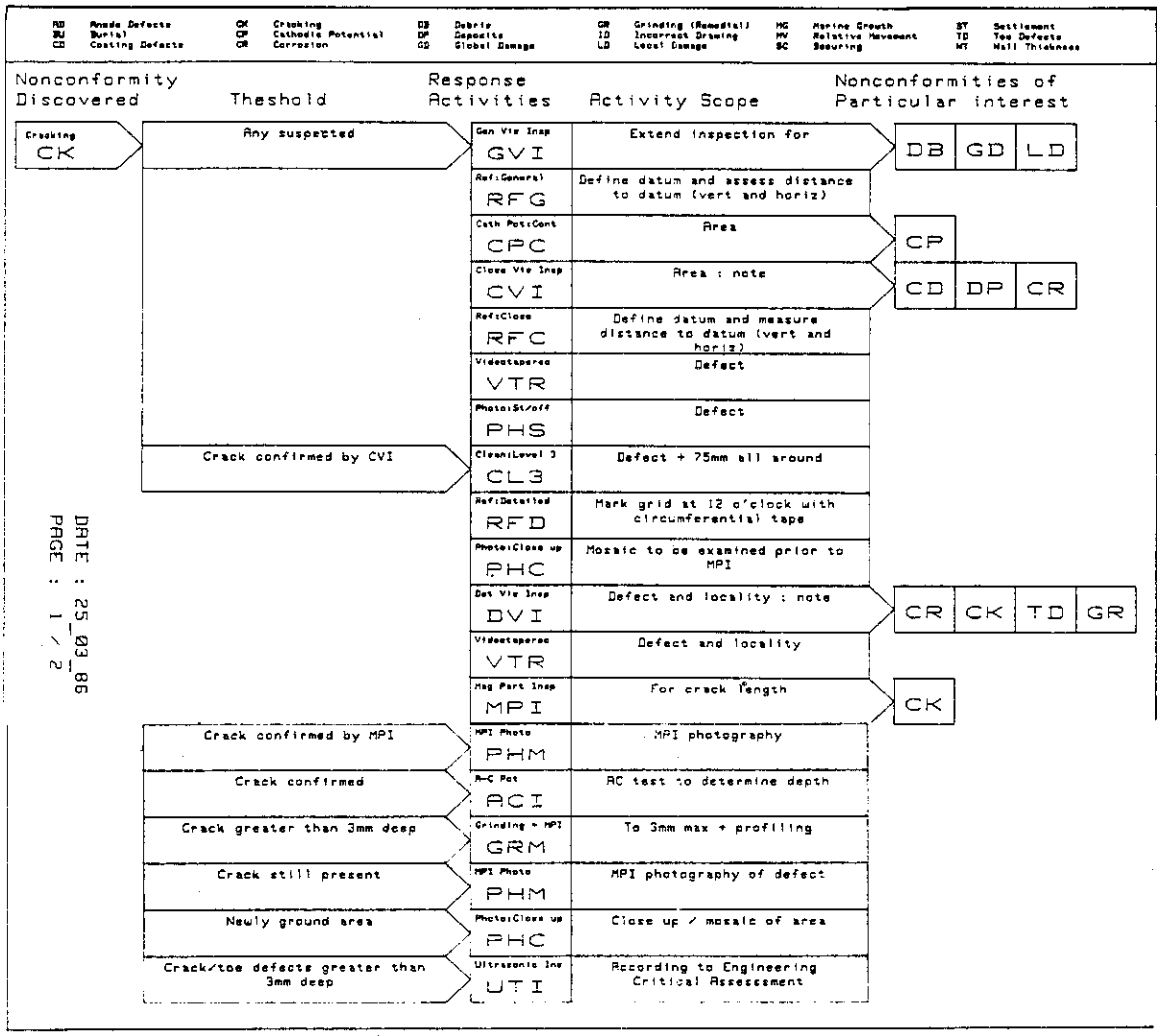


Figure 6.1 *Response activity guidelines*

7 Inspection and monitoring operations

7.1 INTRODUCTION

To acquire and maintain an assurance of the structural integrity of an offshore installation within the constraints of current technology, it is necessary to carry out physical inspections of the structure under water. In order to apply the selected inspection method(s) it is necessary to adopt some form of intervention to get man and/or machines to the inspection site and also necessary to carry out some preparatory cleaning work before inspection. Structural monitoring methods may be used to supplement the chosen inspection methods. All these aspects of the complete inspection operation are introduced below and discussed in more detail in Sections 7.2–7.6.

7.1.1 Inspection methods and techniques

Definitions

Inspection, in the context of offshore installations, can be defined as a set of detailed examinations of a specific area or component in search of major or minor defects, flaws or other conditions through which the integrity of the overall structure can be assessed while in service. The data gathered is considered along with data from previous surveys to provide a level of confidence regarding the structural integrity of individual components of the structure as a whole.

Inspection methods are the generic descriptions of the different ways in which inspections can be carried out (eg magnetic particle inspection, radiography, etc). There are many methods available to the inspection engineer but only a few are currently applicable for underwater inspection. The relevant methods are described in Sections 7.2.1 to 7.2.11. Within each method, different *techniques* define the ways in which the method can be applied. For example, more than 20 different MPI techniques can be defined.

Procedures are required to define an inspection programme. Some procedures are general and some specific but all should be clear, unambiguous and documented.

A procedure specification is relevant only to the specified combination of technique and workpiece; it needs to be modified if either of these is altered. It must be prepared according to the guidance and regulations published by government sources and certifying authorities, it must comply with the operator's own requirements and it must adhere to good established inspection engineering practice and relevant physical principles.

The procedure specification should be prepared by inspection/NDT technologists with relevant academic qualifications and practical experience, not by inspector/diver technicians nor by non-specialist engineers.

Procedure specifications may need approval from the relevant certifying authority. Some may warrant a qualification test to acquire the necessary level of confidence. Approval would then be automatic for all future uses of the technique/workpiece combination.

Personnel

It is essential for the efficient running of an underwater inspection programme that an 'on-site' management structure is clearly understood and that all personnel involved have clearly defined functions and responsibilities:

- *Diving superintendent/senior diving supervisor*
  The diving superintendent is the diving contractor's most senior representative on-site and as such is responsible for the overall conduct of the services being provided.
- *Diving supervisor*
  The diving supervisor is the responsible person for the supervision of diving activities. His/her responsibilities are primarily concerned with the supervision and safety of divers carrying out the work.
- *Underwater inspection controller*
  A person who has undergone specific training on the theory and application of underwater inspection techniques and procedures. He/she is responsible for the topside co-ordination of inspection work being carried out by divers. He/she also assists in planning the implementation of the inspection tasks and reporting the results. In the UK the person would be appropriately qualified to CSWIP 3.4U. These

personnel may be the diving contractor's employees or be independently employed by the operator.

- *Diver inspector*
  A diver who has undergone specific training in the theory and practical application of underwater inspection techniques and procedures. He/she is required to carry out the underwater inspection tasks and prepare reports on the findings. The appropriate qualification for the diver inspector in the UK is CSWIP 3.1U or 3.2U.
- *Operator's offshore representative*
  The on-site representative of the operator, with responsibility for ensuring that work is performed in a safe and efficient manner and is done according to the specifications and requirements of the company.

Categories of inspection methods

The methods of underwater inspection follow a natural progression in that some tasks must be done before others. In addition, some can be done on an uncleaned structure (primarily those to detect gross damage or deterioration) but others can only be carried out after relevant parts of the structure have been cleaned. As a general rule, the simpler, relatively unsophisticated methods are used wherever possible, with steadily more complex (and more expensive) methods following on – to detect and characterise defects not visible to the eye. Table 7.1 outlines inspection tasks, their purposes, the methods used and their places in this hierarchy. Section 7.2 gives more details.

The effectiveness of any proposed method or technique should be assessed before it is used for operational work under water.

7.1.2 Cleaning

The industry survey carried out in Study 1 of this Project (see Section 1.3) indicated that up to approximately 50% of all inspection time is accounted for by cleaning work. Cleaning is therefore a subject of considerable importance as it represents a significant cost to the operator. Inspection methods that do not require prior cleaning can represent a considerable advantage.

Marine growth cleaning carried out in the North Sea is done to reduce wave loading on structures or to prepare for detailed underwater inspection. The cleaning for wave loading reduction involves the removal of coarse marine growth leaving calcarious deposits, whereas detailed inspection requires cleaning to SA 2.5 or sometimes even less, depending on the inspection technique used.

Cleaning methods range from slow simple ones using inexpensive tools to those that are fast andcomplex and rely on expensive equipment. They include:

- wire brushes – hand and powered (Section 7.3.1)
- grinders (Section 7.3.1)
- chipping hammers and needle guns (Section 7.3.1)
- high-pressure water jetting – with and without abrasives (Section 7.3.2)
- cavitation water jetting (Section 7.3.2)
- dry grit blasting.

Cleaning costs are also site dependent; for example, the tidal currents of the southern North Sea make cleaning relatively more expensive in that area.

7.1.3 Intervention methods

There are four methods of getting inspection and cleaning equipment to the underwater location where they are to be used:

- diving – at ambient pressure (Section 7.4.1)
- atmospheric diving suit – ADS (Section 7.4.2)
- manned submersible (Section 7.4.3)
- unmanned remotely operated vehicle – ROV (Section 7.4.4).

The methods are described in Section 7.4, explaining how each places limitations and restrictions on the performance of inspection work. It is important to match the method of intervention with the requirements of an inspection site and of the inspection technique and equipment to be used – to ensure that the characteristics of the method chosen do not interfere with the acquisition of inspection data to a degree that will adversely affect reliability, accuracy and quantity to an unacceptable level. Consideration must also be given to the cost effectiveness of the intervention method chosen.

The most important thing to remember about an intervention method is that it is *only* a means of getting the inspection capability to the worksite; it must not be regarded as an end in itself.

7.1.4 Monitoring operations

In contrast to underwater inspection, which has been defined as 'a set of detail examinations of a specific area or component on an installation' (see Section 7.1.1), monitoring is the continuous surveillance of a specific parameter or parameters of the installation to give a continuing indication of the structure's condition. More specifically, it involves the surveillance of structural elements with sensors or transducers, so that physical effects related to defects can be identified. Assurance can then be provided of the structural integrity of selected load-bearing components and of the whole structure.

The primary objective of any inspection plan or monitoring procedure is to provide assurance of continuous, safe and economic production from an offshore installation. Both inspection and monitoring specialists are in agreement that NDT inspection cannot be displaced entirely by monitoring but that the role of monitoring is to aid inspection, reduce the need for inspection and help avoid serious failures. Because most offshore steel installations are highly redundant structures they can suffer some damage without immediate serious consequences. But damage undetected by inspection – either because of inadequacies in the inspection techniques used or because the damage occurred shortly after one inspection and well before the next – can reduce the reserves of strength contributed by the structural redundancy. The result of the collapse of a load-bearing component would be a redistribution of loads, subjecting the neighbouring components to even greater loads (in some cases even overloads). If such damage is not visually obvious, it could pass undetected for months or never be detected at all. In the extreme case, it could go unnoticed until the next detailed inspection covers the same area, which may be up to five years later. The reduction in the assumed redundancy and possible overloading of neighbouring elements may trigger a sequence of events which in turn could lead to serious cumulative damage. By contrast, it is claimed that structural monitoring using vibration measurement techniques, for example, can detect member severance *at any time* and can even determine the approximate position of the damage.

It is possible to envisage two extremes of the monitoring process:

- a 'qualitative' (go/no-go) system – which monitors whether a change has occurred (eg in stiffness) without locating or quantifying the change
- a 'quantitative' system – which besides indicating that a change has occurred also defines the location and extent of the change. A system of this sort requires relatively more sensors than a qualitative system.

In addition, when monitoring systems were first developed, they were envisaged as being used globally throughout all areas of a structure and permanently throughout the life of the structure. It is now realised that monitoring can be far more flexible:

- *Sensitivity*
  The system may be designed to respond only to major defects, such as member severance or through-thickness cracks. In extreme circumstances and depending on the degree of redundancy, such a system may only give adequate warning to prevent loss of life and allow limited recovery of equipment.
  A system with much finer sensitivity would be expected to give sufficiently accurate information on defect size (and even location in many instances) to ensure ample time for optimum remedial action to be taken.
  In a 'tuned' monitoring system, unwanted parameters in the data (eg data related to crack opening and closing) would be filtered out and ignored, with only the data relating to crack propagation being recorded. Alternatively, a defect once detected (by either monitoring or physical inspection) could be closely monitored by additional sensors temporarily installed to provide further detailed data. These sensors might be similar to existing ones to extend coverage, or of a different type to measure additional parameters (eg AC potential difference electrodes to measure crack depth propagation). The extra data obtainable from this tuned monitoring would be used as an aid in planning remedial work and/or repair.

- *Coverage*
  Global monitoring (ie monitoring covering the whole installation), although desirable in the long term, is not essential in the short term. There may be very considerable benefit to be gained by only monitoring specific areas of interest. A simple local system operating at coarse sensitivity need not be expensive or difficult to install and operate. Should a defect be detected by monitoring of this sort (or any other means, including a physical inspection), the addition of more sensors can relatively easily extend the coverage or 'tune' its sensitivity (see above).
- *Continuous or occasional use*
  Monitoring may be used on a temporary basis only, usually with local coverage and fine or tuned sensitivity. Such systems may be used to monitor a previous repair, a suspected defect, an area with some doubt in the stress analysis, or for some other similar specific purpose.
  It may also be beneficial to use monitoring to supplement or otherwise partially replace some aspect of physical inspection. For example, if it is accepted that a crack below a specified size is of no particular relevance (under the duty and load conditions expected) and a monitoring method can be relied upon to provide better than that level of sensitivity, then the system may be acceptable for use throughout the structure's life but only at specified periods. There are many scenarios under which such periodic monitoring may be of value, including during winter (bad weather) months and during the development of inspection programmes.
  Systems may also be engineered for permanent duty over the lifetime of a structure. A permanent system need not necessarily be of fine sensitivity or give global coverage; it may, for example, provide invaluable data even if it is restricted to coarse sensitivity and localised coverage.

The monitoring systems available are described in detail in Section 7.5. In Section 7.5.1, the essential components of any monitoring systems – equipment for data acquisition, transmission, processing and recording – are firstly discussed. The systems themselves involve monitoring of:

- structural vibration (Section 7.5.2)
- acoustic emission (Section 7.5.3)
- cathodic protection condition (Section 7.5.4)
- steelwork internal pressures (Section 7.5.5)
- local cracking – with fibre-optics (Section 7.5.6)
- performance (compared with design predictions) (Section 7.5.7)
- propagation of known cracks (Section 7.5.8)
- member flooding (Section 7.5.9).

7.1.5 Influence of water depth and structure type

The descriptions and discussions of inspection and monitoring methods in Sections 7.2 to 7.5 concentrate on the requirements of the primary structure, ie the loadbearing portion[7.1], of a steel jacket platform. In addition, however, a platform contains secondary structures which are essential to the installation but not loadbearing in the same sense as the primary structure (eg export risers and conductors) and secondary components and attachments which are personal safety and convenience features (eg boat landings, bumpers, fenders and hand rails).

Section 7.6 describes the special inspection requirements of these secondary structures and components as well as the requirements for the primary components of non-platform installations, eg tension leg platforms and pipelines, wellheads, templates and manifolds on the sea bed. The methods and techniques used are similar to those used on primary jacket structures but the emphasis of their application is different.

Table 7.1: *The hierarchy of underwater inspection tasks on steel structures*

Inspection task	Description	Methods used
Inspection requiring no cleaning		
General visual survey	May be included in the tasks below, but is sometimes separated	Visual inspection with video and stills photography (Section 7.2.1)
Debris survey	Note and record debris on the installation (usually included in 'general visual survey' above)	Visual inspection (Section 7.2.1)
Marine growth survey	Measure distributions and thicknesses of different types of growth (see Reference 7.1.1)	Photographic and tape measure surveys
Seabed survey	Detect and record debris on seabed. Check soil levels, scouring, scour prevention devices, evidence of instability	Visual inspection (Section 7.2.1)
Cathodic protection survey	Measure cathodic protection potentials Measure depletion of anodes Check electrical continuities Measure current flux densities Check coatings Note and measure evidence of pitting Measure wall thicknesses (some local cleaning may be necessary)	CP checking (Section 7.2.2) Visual and tape measurements Visual inspection Current density meter Visual inspection Visual inspection and thickness measurements (Section 7.2.3)
Flooded member detection survey	Check tubular members to detect water ingress (some local cleaning of coarse marine growth may be necessary)	Flooded member detection (Section 7.2.6)
Inspection requiring cleaning		
Close visual inspection	Inspect nominated areas for visible damage, particularly cracking and corrosion damage	Visual inspection (Section 7.2.1)
NDT inspections	Inspect nominated areas for damage (ie the presence of cracking and corrosion) using appropriate methods and techniques (Some grinding is likely to be necessary to help in interpretation of results)	Magnetic particle inspection (Section 7.2.4) Flooded member detection (Section 7.2.6) Radiography (Section 7.2.7) Eddy current testing (Section 7.2.8)
Further NDT and inspection	Establish the length, depth and exact location of crack-like defects Establish the metrology of dents, buckles and other deformations	Shearwave ultrasonic methods (Section 7.2.5) Alternating current potential drop method (Section 7.2.9) Photogrammetry (Section 7.2.10) Taut wire measurement Profile gauging

This schedule does not include all inspection tasks; specialist tasks such as checking grout fills must be carried out as necessary

7.2 INSPECTION METHODS

7.2.1 Visual inspection

The major part of any underwater inspection programme is usually based on visual examinations. The techniques used are:

- a diver using his own eyes (and his associated powers of interpretation)
- still photography
- closed-circuit television to the topside (CCTV or video).

Constraints of visual inspection

The underlying, if obvious, limitation of all visual inspection methods is that only defects large and clear enough to be visible can be detected. There is also an important difference between 'seeing' and 'finding'; it may be possible for an inspector to *see* a defect once its exact location is pointed out to him, although he was not able to *find* it unaided.

Visual inspection is significantly affected by the underwater environment. Ambient lighting is attenuated with depth by the effects of suspended solids and algae, and artificial lighting should always be used for photography and usually for video. The refraction of light passing from water to air changes image sizes and perspectives and alters colour balances, and the depth of the water above an inspection site acts as a colour filter, further affecting colour balances.

Equally important, the effectiveness of visual inspection by a diver inspector is dependent on the overall ability of the diver making the observations and the dialogue between him and the inspection controller.

Divers versus ROVs

The size of offshore structures and advances in ROV (remotely operated vehicle) technology have meant that divers are now rarely used for large-scale visual surveys of a structure; they can be more usefully employed in specific areas. ROVs allow large areas to be covered quickly and effectively and full control of the survey rests with the surface personnel. This has resulted in increasingly stringent qualifications for the personnel involved and the creation of a CSWIP system of qualifications similar to those of diving inspectors.

The major drawback to ROV visual inspections is the accumulation of marine growth, which can completely obscure even large features. If ROVs are used in areas of heavy marine fouling then only the grossest of defects, such as badly deflected or dented members, will be reported. A diver is able to hand clean the worst of marine growth and hence is able to locate much smaller defects. The time required for cleaning does however limit what can be done and thus diver visual inspection is normally limited to specific areas.

Divers also have the advantage that they often see much more of an area than an ROV. Because of this, they often find defects whilst engaged on other tasks. A divers three-dimensional vision also enables better interpretation of a visual image. Although stereo-video is available for ROVs it has been little used to date. The respective capabilities of divers and ROVs are further discussed in Section 7.4.

Recording

Most diver inspections are augmented by the use of a head-mounted video camera because all visual inspections are very much more effective if the inspection controller on the surface has some idea of exactly what the diver is seeing. The camera allows surface personnel to follow a diver's actions, know where he is and have a much clearer idea of what he is describing. Without such a camera, much time can be lost in misunderstandings between the diver and surface personnel, particularly when something completely unexpected is found.

Permanent records of visual inspections are normally written reports augmented by either video recordings or still photographs. Both depend on accurate written or verbal descriptions of orientation, views and features. Video recordings, whether made by diver or ROV, must have clear and concise descriptions of locations and viewing directions – with divers these can come direct from the man on the spot, with ROVs they rely on the data recorder/pilot.

ROVs are usually unable to place identification plaques or descriptive labels in their photographs, and scale rulers can only be manouvered into position if mounted on long prods – which may then obscure details. To overcome these limitations, camera systems can be used with surface-controlled data chambers which print text onto each photograph, and stereo cameras suitable for photogrammetry may be employed. The framing of ROV photographs can also be difficult because of the parallax between video and stills cameras. Several combined stills and video systems are now available although they are generally too large for fitting to the smaller ROVs.

Diver photography does not suffer from these problems. Even if the camera system has no viewfinder, the field of view can easily be estimated. Close-up photography, particularly of welds, requires extensive identification and can at the moment only be performed by divers.

Developments

Stereo-video and stereo-photography are areas which offer much improved capability. A stereo-video system would give impressions of depth and space to ROV pilots and other viewers. Stereo-photography is more straightforward and several systems already exist. The technique's greatest asset is in photogrammetric analysis of stereo pairs which allows physical distances to be derived from the photographs. (See Section 7.2.10).

7.2.2 Cathodic protection checking

CP potential

Measurement of the steel/seawater potential on the submerged structure is an important requirement, to confirm that the level of corrosion protection provided by the cathodic protection (CP) system is adequate.

Measurements of potential are made relative to a reference electrode, commonly a silver/silver chloride (Ag/AgCl) half cell. As a general guideline, steel with a potential more negative than –0.8V relative to Ag/AgCl is adequately protected, but the nature of CP measurements is complex and they should be carefully evaluated. Simple potential measurements indicate the adequacy of protection at a given point and time; a point only 1 or 2 m away may be grossly under-protected. The classic example of under-protection in the North Sea results when a CP system is designed on the assumption that pile guides will be removed after installation. If the guides are not removed, the additional steelwork is under-protected and may act as a drain on the surrounding CP system, leading to corrosion not only of the pile guides but also of the structural steelwork to which they are attached.

The following methods are employed to obtain CP potential measurements:

- By contact, where the Ag/AgCl half cell is hand-held by the diver or mounted on an ROV. Measurements are taken when a metallic probe on the measuring instrument touches the surface of the steel. This method has the advantage that each measurement is taken with the half cell at a fixed stand-off distance from the steelwork, but the disadvantage that the probe must be brought into imtimate contact with the steel, possibly necessitating some limited cleaning.
- With a 'proximity reading', whereby the connection with the structure is made above water or at some other convenient point and the half cell is moved to the measurement locations by ROV or diver. This method has the advantage that many readings may be taken rapidly and over large areas; it is common for ROV surveys of fixed platforms to have a continuous readout of potential recorded on the video image. Its disadvantages are that probe stand-off is rarely constant and that the earth connection has to be moved if different parts of the structure are electrically insulated. (This technique is also suitable for monitoring reinforcing steel in concrete structures.)
- On pipelines, a remote anode (ie one oustide the influence of any steelwork or CP systems in the vicinity) is often used as a constant reference in place of completing the circuit to the protected steelwork. Contact readings are however taken where possible.
- By using fixed reference electrodes which transfer signals either by cables or acoustically to a transponder lowered into the sea. This diminishes the need for divers or ROVs, and is particularly suited to subsea templates and equipment where grounding is not possible.

Current density

The measurements described above indicate only whether the structure is sufficiently cathodic to be protected from electrolytic corrosion. By using more elaborate equipment the current density being generated by any sacrificial anodes or being impressed on the steelwork may be obtained. This information, coupled with knowledge of the anode material, allows an accurate evaluation of the CP system, including estimation of anode life, possible shadow areas, etc. However, the necessary extensive measurements and computer modelling can be costly. For this reason, little use has been made of this technique on fixed installations in UK waters. An exception is CP modelling for pipeline survey where, due to the simple and repetitive nature of this type of installation, quite detailed information is relatively easily obtained.

Some operators have experienced difficulty in obtaining repeatability of results and the associated confidence in data accuracy. These problems can only be eliminated by more careful calibration and data processing than has sometimes been used.

Measurements have most often been acquired as part of ROV inspections, and there is reason to believe that this procedure will increase in the future. Furthermore, there is every reason to combine CP potential and current density measurement capability into one meter, enabling both readings to be made concurrently with no additional cost or time penalty.

7.2.3 Thickness measurements

Ultrasonic techniques

Measurement of steel wall thicknesses underwater is normally carried out using ultrasonic pulse-echo compression-wave techniques and equipment. A pulse of ultrasound is generated in a piezoelectric crystal, passes into the steel surface and reflects from the back wall. The time delay (t) between the input pulse entering the steel and the return echo from the back wall can be measured, and the wall thickness of the steel determined using the appropriate value of ultrasound velocity (V) for compression wave propagation, ie:

$$\text{wall thickness} = \frac{t \times V}{2}$$

Application of the technique for spot checking of wall thickness is normally done with a digital instrument. There are a number of commercially available instruments on the market for use under water. They rely on a single or twin crystal probe, generally in the frequency range 2.5–5 MHz, but differ in the averaging methods they use to produce stable readings, ease of calibration, housing type and (from a practical viewpoint the most important area of difference) the probe configuration. Some units have a remote probe, mounted on a wander lead connected to the electronics/readout housing. They can be very useful in areas inaccessible to the complete unit (eg underneath pipes on the sea bed) but suffer from the disadvantage of a two-handed operation – not easy for a diver attempting to hold position on a vertical structural member.

The instruments require the steel surface to be cleaned to a smooth surface, although some are capable of taking readings through a surface coating. A rough surface, eg a severely corroded surface, reflects a large portion of the input energy and may mean that measurements are impossible with standard equipment.

Although these instruments are in widespread use, and have been significantly improved in recent years, there still remains considerable doubt about the accuracy of the measurements in some circumstances. The output is nothing more than an estimate of the depth of the strongest acoustic reflector which may or may not be the backwall. Furthermore, digital instruments give no information about the corrosion state of the material under test. They are therefore suitable for spot checks, but are not normally used for scanning large areas where specific problems such as corrosion are anticipated.

For such applications, and where a manual survey is to be carried out, 'A'-scan ultrasonic equipment is normally used. It requires a much higher degree of skill than the digital equipment since the operator must calibrate the equipment and interpret an oscilloscope image. These techniques are included in the CSWIP 3.2U examination. The equipment allows the inspector/diver manually to make a map of laminations or corrosion. Equipment also exists to allow automatic mapping of wall thickness, using a scanner (which moves the ultrasonic probe) linked to topside control equipment. Scanner position and wall-thickness information is stored and processed in a computer, allowing thickness maps made on one occasion to be repeated later for comparison purposes.

Corrosion pits

The probe on standard ultrasonic equipment is not able to reach the bottom of a corrosion pit, and hence cannot make measurements of the pit or the remaining steel wall thickness under it.

The most common method of recording pit dimensions is to cast on site a replica of the pit which, when brought to the surface, can be studied and measured in detail. Pit replicas (or moulds) are usually made using a rubber compound which is sufficiently stable after curing to be removed without damage. The major problems with this method are 'mess' for the diver and long curing times (sometimes around 12 hours), although more rapid curing is possible by using a compound which cures under ultraviolet radiation. One available method claims sensitivity such that replication of the actual grain structure is possible. The method is also used to make replicas of cracking, other damage and MPI indications, all of which can prove valuable when making a topside assessment of underwater damage or deterioration.

Although mechanical pit-depth gauges are also available, they only produce accurate results if the gauge point is sharp enough to reach the bottom of the pit. In practice, the potential error from this shortcoming is considerable.

Pit depth can also be measured using ultrasonic techniques where a focused ultrasonic beam (of 1–2 mm diameter) is positioned to enter the steel surface where the corrosion pit is deepest. The principle of operation is illustrated in Figure 7.1 where ultrasonic equipment capable of being used for this purpose is being used to measure remaining ligament thickness of a weldment after remedial grinding. This device can also be used to measure the remaining wall thickness in the base of a corrosion pit. The equipment shown in the Figure has been further developed and now offers a digital display format instead of the A-scan type display shown.

Photogrammetry may also be used to determine pit depth.

7.2.4 Magnetic particle inspection

The magnetic particle inspection (MPI) method of inspection has been used under water for many years. It is the most commonly used NDT method for detecting surface-breaking defects in welds and is easily carried out using equipment that is well proven.

The principle is simple. If a magnetic flux parallel to the surface of a component encounters a discontinuity, the flux becomes distorted – part passes through the crack, part is diverted internally around the tip and part bridges the crack at the surface. This bridging flux (termed leakage) attracts ferromagnetic particles which are applied to the surface of the steel in a liquid suspension. The resulting concentration of particles at the crack opening (an 'MPI indication') delineates the crack.

Under water, the diver magnetises the weld using one of the methods described in 'Magnetic flux' below. Once the flux is present, fluorescent magnetic particles are applied to the area and an ultraviolet light source used for illumination. The diver reports his findings via the communications link to the inspection controller at the surface and often the results are photographed using specialised techniques.

Theoretically, defects of 3–5 mm in length can be detected. In practice, many factors affect the detectability, including:

- *magnetic flux*
  adequacy and position within the test material
  strength*
  orientation with respect to the likely direction of cracks**
- *indicating particles*
  size
  permeability
  retentivity
- *viewing and illumination conditions*
  background contrast
  ambient lighting
  particle illumination.

* The intensity of the magnetic flux must be sufficient to produce the leakage flux but too high a level can lead to saturation of the test area. Defects are masked if the metal is saturated as even the slightest irregularity begins to produce leakage flux.

** For a defect to be detected there must be leakage of magnetic flux from the surface of the test area. The defect must therefore have sufficient length and depth to create a detectable leakage flux but the direction of the flux in relation to the orientation of the defect is also significant. An angle of 90 degrees between the two gives the best detectability, and a minimal effect results when they are parallel.

Magnetic flux

In underwater work, the magnetic flux can be induced in the test area in broadly similar ways to those used for land-based MPI although there are some differences in the techniques used.

The insulated coil and conductor technique has largely been developed in response to the special requirements of the underwater industry. It relies on current-carrying coils which can either encircle an area (particularly member ends) or sit astride the test area. More than 80% of North Sea operators now use this technique frequently; it is the first choice for all except the smallest or most specialised test areas. Its advantages include rapid use, repeatable results (if used correctly) and simplicity. The applied magnetic field can be adjusted via surface controls. There is no risk of arcing (see 'prods' below), a continuous inspection can be made once the coil is set up and demagnetisation is easy. Its major drawback is the size and weight of the underwater transformer used and the time required to get it to the worksite and then encircle the test area. The most commonly used transformer weighs 57 kg in air (26 kg in water) and has a 13-m cable rated to 1000 A. This unit must be positioned under water to within 2 m of the test area to allow full use of the ultraviolet lamp and ink dispenser. Detectability is low for cracking which is transverse to the direction of coil winding (ie parallel to the flux lines) but at a maximum for cracking parallel to the conductors. There is a risk that users of this technique with a restricted understanding of its theoretical background may mis-use it or not use it to the full potential. With a proper theoretical input, there is virtually no underwater steel component that cannot be inspected effectively, even fillet welds on gussets and other difficult-access areas.

Flux flow techniques of magnetisation using horseshoe or articulated permanent or electro-magnets are generally only suitable for small test areas mainly because of the inherent slow inspection rate. There is also difficulty in ensuring good contact between the pole pieces and test surfaces. Magnets should not be used on curved test surfaces without special and justifiable reasons.

Current flow techniques where the current actually passes through the test steel are performed on land with lead-tipped prods or by using large fixed machines with contact heads which introduce the current to the test area. Underwater, only the prod method is possible and it was at one time the standard magnetisation technique for underwater MPI. It is now recognised to be significantly slower than insulated conductor techniques and prone to inducing micro-cracks through arcing at the contact points. It is also difficult for a weightless diver to apply adequate contact pressure between prod and steel surface. In its defence it must be said that it is a technique where the magnetic flux density can easily be assessed. It is still in limited use in the North Sea – in the Norwegian sector.

Ideally a flux meter should be used to confirm that the correct level of flux is present in the steel for optimum defect detection, but the most common technique is calculation backed up by a field strength indicator such as Burmah-Castrol strips or ASME varieties. These indicators contain a series of artificial discontinuities and it is assumed that there is sufficient flux when a specified number of them are visible. Strips are available which have been designed for underwater use; they can be manipulated by a diver's gloved hand and are relevant to the Grade 50D steel used for many offshore structures, but they must be used with great care. Theoretically, they give flux levels close to the saturation in Grade 50D steels, but operational experience has shown that saturation is not generally a problem, particularly when the field is generated by a coil that has the maximum number of turns and carries minimum current.

Reliable crack detection requires that the flux density is within a given range. BS 6072[7.2] (which is not written with underwater application in mind) specifies a minimum flux level of 0.72 tesla. The flux (B) is dependent on the magnetic permeability (μ) of the steel and is related to the applied magnetising force (H) by the formula $B = \mu H$. BS 6072 assumes a value of 240 for μ, which implies a minimum H of 2400 $\mathrm{Am^{-1}}$. Recent work has shown that Grade 50D steels have a much higher value of μ, typically in the range 700–1000. Hence a lower magnetising force H (and therefore current) is actually required, of around 1000 $\mathrm{Am^{-1}}$.

Defect indications

On land, contrast paint and black magnetic particles are commonly used to ensure maximum defect visibility. Contrast paint would be difficult to apply under water, so fluorescent magnetic inks which emit visible light when exposed to ultraviolet radiation are used. The result has been that underwater MPI has been carried out at night, generally in ambient light levels of less than 10 lux. Better fluorescent inks are now becoming available which are visible in higher ambient light levels and it is likely that this will be an area of progress once operator confidence has been established. This is particularly important as inspection on North Sea structures is restricted to the summer months and many northern platforms have short darkness periods at this time of the year.

Flourescent inks used in these low ambient light conditions give very high contrast and should, theoretically, enable very small defects to be detected. However the conditions under which underwater MPI is conducted are difficult and, in spite of the fact that CSWIP Phase 7 qualified diver/operators are nearly always used for underwater MPI work, a survey of operator opinions showed that the mean length of the shortest crack that could reliably be detected was 29 mm. This is many times the theoretical minimum detectable size, but it does still show a fairly high degree of confidence amongst operators that they can detect significant defects in areas examined by the MPI method.

Defect recording and assessment

Findings are generally reported via the inspection controller at the surface. The obvious drawback is that, even for a critical weld, the engineer is unable to see the indications; he has to rely totally on the skill and experience of the diver. Appropriate photographic techniques – relying on a modified underwater flash unit with appropriate filtering to suit the fluorescence of the particles – can help in this respect. High quality still photographs then provide the engineer with additional information regarding the shape and distribution of the indications, and can assist in distinguishing between fatigue cracks and spurious indications such as weld undercut. The technique is sufficiently reproducible for crack monitoring purposes. It is still relatively common offshore practice to drill crack arrestor holes at the ends of a fatigue crack, as a temporary means of repair. MPI photography can be used to confirm that the indications are still contained by the holes and that no change in the shape of indications has occurred.

Other techniques are also used. The practice of proof grinding of indications is still the most commonly used method but underwater AC-PD equipment used to measure crack depths (see Section 7.2.9) has been used despite some technical drawbacks.

In proof grinding the diver/inspector grinds small increments of metal from the area of the indication, usually to a maximum depth of 2 mm. If the defect still exists, it is then usually considered to be a crack and to justify further investigation. This technique may well result in more use of grinding than is strictly necessary, but the general smoothing of the inspected surface must increase its fatigue strength and for that reason it finds almost universal favour amongst operators.

7.2.5 Ultrasonic defect characterisation

Amplitude techniques

Shearwave ultrasonic methods are used under water to characterise crack-like defects (eg fatigue cracks) once they have been detected by other inspection methods. The ultrasound is introduced into the metal at an angle to its surface so that a suspect region is examined from its side. For optimum defect detection it is essential that the correct ultrasonic probes are used (the angle, frequency and beam width are to be considered) and that the procedure adopted is appropriate for the defects to be detected.

The most common method of defect sizing using shearwave ultrasonics is by amplitude monitoring, where the probe scans across the surface and maximises the defect signals it receives. By adopting an amplitude-drop technique, and referencing results back to curves or beam profile plots, measurements of the defect can be obtained. The technique can be used to characterise non-surface-breaking as well as surface-breaking defects.

'Automated' shearwave equipment is available to work on simple butt welds in pipes. It does this very effectively but is not yet suitable for the variable geometry of jacket nodes.

One system developed to improve the application of manual ultrasonic testing under water locates the bulk of the instrumentation topside and fits the diver's helmet with a hat-mounted TV camera (HMTV) and a head-up display unit. The HMTV provides the surface controller with a picture/video of the probe position, etc and the head-up display provides the diver with a picture of the A-scan display transmitted from the topside ultrasonic set.

The diver has only to take the ultrasonic probe under water and is not required to operate/adjust the ultrasonic set as this is done by the topsides operator on the diver's instruction.

The accuracy of conventional shearwave ultrasonic inspection has been the subject of much debate during recent years. Experimental programmes carried out by the nuclear industry demonstrate that accuracy is highly dependent on the skill of the operator, as well as on parameters such as ultrasonic equipment characteristics, defect position and shape, and material surface finish. An operator can only be expected to size a fatigue crack in the laboratory in air to within ±3 or 4 mm of its true depth. Bearing in mind the extra difficulties encountered under water, this represents and unacceptable degree of error for practical use.

The main disadvantages of the amplitude techniques are:

- the contact pressure of the ultrasonic probe on the steel surface must be constant (if it is not, large variations in amplitude values can occur)
- changes in the cross-section area of the defect cause changes in echo height, which may cause confusion in interpreting the defect signal
- false or misleading indications may result if the defect is unfavourably oriented or positioned and only limited access is available
- a change in the axis or orientation of the defect can also cause problems
- slight twisting of the probe during scanning can lead to false indications
- a change in surface roughness can produce large anomalies.

The time-of-flight diffraction technique (see below) overcomes some of these problems.

Time-of-flight diffraction (TOFD) technique

TOFD relies on the measurement of signal time differences between known paths and those of defects; it places little or no reliance on signal amplitudes and so is less sensitive than amplitude techniques to the condition of the steel surface or operator performance. An ultrasonic pulse is introduced into the steel surface at one point and diffracted signals are received, recorded and interpreted by a receiver placed at the same or a different point. Accurate measurement of the geometry of the steel under test provides the necessary data to locate and size any defects (hidden and surface-breaking) by interpreting the arrival times of the signals. The technique is particularly useful for the sizing of known defects such as surface-breaking cracks, but can also be used with considerable benefit in a 'search' mode to locate unknown defects.

Diffraction signals are visible over a much larger range of probe angles than are the reflected signals of pulse-echo techniques. Thus TOFD detects defects over a wider range of orientatious than conventional ultrasonic methods, but ultrasound frequency and probe disposition must be selected with care to suit crack and worksite geometries. Clear operating procedures must be laid down and followed if TOFD techniques are to be used successfully, in a reliable and repeatable manner.

7.2.6 Flooded member detection

Flooded member detection enables the rapid screening of jacket structures for the detection of water ingress into structural members, to give an indication of the presence of through-wall defects. Since steel jackets comprise a space frame of sealed tubular members containing air at atmospheric pressure, flooding will occur if a fatigue crack penetrates the wall thickness of a submerged tubular.

Figure 7.2 depicts a flooding detection system in operation, attached to an air-filled member and a flooded member respectively. The ultrasonic probe emits short bursts of ultrasound energy due to excitation by electrical signals sent via the signal cable from the instrumentation package on the surface. The transducers are aligned by the diver so that the ultrasound pulses are transmitted normal to the member front face. When the ultrasound signal reflected from the front face of the member is maximised, the transducer is aligned correctly. Due to the poor transmission of sound energy across a steel-air interface on the inside of the member and the high attenuation of sound in air, the transducer on the air-filled member only receives echoes reflected from the front face of the member. The signals received in this case are shown on the left hand display. However, the transducer on the flooded member receives echoes from both the front and back faces of the member because of the good transmission of the ultrasound across the steel-water interface, coupled with the low attenuation characteristic of water. The resulting echoes received from this transducer are shown on the right hand display, from which it can be seen that the presence of the back face echo is an unambiguous indication of a flooded member.

The position of the back face echo on the screen varies according to the diameter of the member being inspected (ie the distance the ultrasound pulse travels). To make interpretation of the echoes easier for the operator, the expected position can be dialled into the display on one commercially available flooded member detector.

Experience has demonstrated the effectiveness and reliability of the technique providing it is applied and calibrated correctly. Problems have been due to incorrect application of the equipment and a limited understanding of the technique by its users. Such problems could be reduced by incorporating education/training in flooding detection techniques within the diver inspection training courses CSWIP 3.1U, 3.2U and 3.4U.

As well as flooded member detectors which operate on the ultrasonic principle, there is a device which utilises a neutron source (1 x Curie, Americium 241/Beryllium) and relies on the detection of back-scattered radiation to detect the presence of flooding.

An obvious limitation of flooded member detection is that some members, particularly jacket legs, are already water or composite/grout filled by design or due to repair. In these situations only the air-filled member side of a weld can be monitored by the application of flooded member detection.

Where flooding is detected, a more detailed inspection (initially of the tubular joint welds) can be undertaken to locate and identify the defect causing the flooding. If no defects are found in the tubular joint welds, other associated weldments and the body of the tubular need to be inspected to detect the cause of flooding. The sequence of inspection is usually:

- nodal attachment welds
- appurtenance attachment welds
- girth and seam welds
- member body.

7.2.7 Radiography

Radiography is used for underwater inspection in a similar manner to radiography on the surface. The principle is simple and widely understood. Material to be radiographed is placed between a source of radiation and a photosensitive film or a fluorescent screen for real-time viewing. As the intensity of radiation attennuates according to the thickness and radiographic density of the material through which it travels, subtle variations (of the order of 2%) in material thickness, density or quality result in corresponding variations of radiation strength emerging and recorded at the receiver.

The radiation sources used in normal industrial radiography are x-ray generators or radioactive isotopes, such as Iridium, Caesium and Cobalt, which emit γ-rays. Although x–rays have occasionally been used under water, the γ sources have been used most commonly. Iridium 192 is the most frequently used isotope, although higher energy Cobalt 60 has been used on thicker wall sections (up to 150 mm). Caesium 132 is not used under water as its energy level is rarely appropriate to subsea applications.

The shielding affect of water (150 mm of water has approximately the same effect as 25 mm of steel) ensures that γ radiography is inherently safer in water than air. However, this attenuation by water means that contact techniques are the only ones possible for 'in-water' radiography (see below).

Habitat radiography

Underwater welded repairs made in habitats must normally be inspected for integrity. The most common NDT methods used are radiography and ultrasonics (for sub-surface, volumetric defects) and MPI (for surface-breaking defects).

The radiation source for the radiography has always been Iridium 192 of activity level up to 50 curies, and it is essential to follow standard safety procedures in the habitat during the exposures. Processing of the exposed film takes place on the surface in the normal way.

The majority, but not all, of the radiography carried out under water has been in dry habitats.

In-water radiography

In-water radiography is almost always restricted to pipes and similar work-pieces. It is essential that the pipe is not flooded, as the presence of a fluid would degrade the image quality to the point where the output was meaningless. The techniques used on land where the energy source is some distance from the steel surface cannot be used in water (because of the attenuation of radiation in water); the technique used is one where the source is positioned against one side of the pipe with the film on the opposite side. Sources up to 200 curies are used and the film cassette must, of course, be waterproof.

Figure 7.3 illustrates two uses of this technique – to detect internal corrosion/erosion of a pipe and to detect internal pipe blocking (eg by waxing). It can also be used for inspecting welds for internal defects.

It is inherently unsuitable for fatigue crack detection; although cracks may be detected in the course of radiographing new welds, others are just as often missed. Confidence in radiography for in-water detection of fatigue cracks is potentially quite dangerous. Radiography can only detect cracks when the crack and radiation axes are coincident or when the crack is large (ie about finger width) in which case it would be visually detectable if surface breaking. In general terms, this means that radiography is sensitive to volumetric defects and root defects, but is insensitive to laminar defects and to cracking where the crack orientation is not coincident with the radiation.

As with all radiography, confidence should never be placed in the fact that a crack may be found; but on the stronger probability that the technique is not finding others.

If real-time radiography can be developed for in-water use, these limitations may be reduced. With real-time radiography, film is replaced as the receiver with some form of scintillating screen (normally fluorescing). Resolution may not be as good as film but it would be possible continually to change the relative positions of radiation source and receptor screen. This should significantly improve the probability of getting the radiation axis coincident with the axis of a crack.

7.2.8 Eddy current testing

The use of eddy current techniques to detect both surface-breaking and buried defects is well established for use on land-based structures. Eddy current defect detection is based on the principles of electromagnetic induction, and is concerned with the interaction of defects in metallic components with the magnetic field generated by a coil carrying an alternating current. When a coil (ie an eddy current inspection probe) carrying an alternating current is placed close to or on the surface of a conductor, such as steel, eddy currents are induced in the conductor material due to the alternating flux produced by the coil. The induced eddy currents in turn produce an alternating magnetic flux which opposes the field produced by the current-carrying coil and this effect is detected as a change in the electrical impedance of the coil which can be measured electronically. Alternatively, the effect of the flux produced by the eddy currents is detected by monitoring the voltage induced in a second coil similar to the excitation coil. As the magnitude of eddy currents induced into the conductor is a function of its magnetic permeability and electrical conductivity, any changes in these characteristics are seen as a change in the impedance of the coil or the voltage induced into a secondary coil. Similarly, any effective changes in these characteristics – due to cracking, surface pitting or inclusions – can be detected.

The technique has been available for a few years and is now becoming more acceptable to the offshore industry. It is currently seen as a method of crack detection secondary to magnetic particle inspection but if sufficient confidence can be created it may eventually replace MPI for this task.

Underwater eddy current equipment comprises a diver-operated hand unit (containing the exciting coil and signal amplifier) connected by umbilical to surface equipment for processing the signal and displaying the output on a vector display CRT. The equipment is calibrated by examining a test-piece containing a series of surface notches of known dimensions. During operational use, the diver gets an acoustic feedback from the signal processor telling him when an out-of-phase signal greater than a pre-set limit has been recorded on the CRT. His only role is to move the hand unit over the test surface and he need have no special experience or training in eddy current testing. However, the surface operator must be trained and skilled – he adjusts sensitivity and vector rotation and interprets and records the CRT display.

Because the exciting energy is high frequency, penetration into the steel is shallow and eddy current testing cannot generally be used for depth measurement or detecting defects more than 5 mm below the material surface ie at depths greater than the 'skin depth'. For defects within the skin depth the change in impedance seen by the inspection probe is proportional to the depth of the defect. For this reason, eddy current systems can be used in certain applications to detect and size defects in metals.

To date there have been a number of attempts to use eddy current techniques for inspection of the submerged steelwork of offshore structures. The success of these attempts has been variable. However, it is evident that this method of inspection is potentially capable of being developed into a rapid scanning technique for underwater use on as-welded components. The main problems to be overcome are:

- material variations (ie magnetic permeability, μ, and electrical conductivity, σ) in particular in welded regions
- compensating for signals caused by inadvertent lift-off of the probe from the surface being scanned and effect of geometry changes
- unambiguous identification of the signal effects caused by a defect rather than material variations, lift-off and geometry changes.

Uses of the technique include:

- *measurement of paint or coating thicknesses* – on identical or known materials, changes in lift-off can be quantified in order to give thicknesses of non-metallic coatings
- *metal identification* – with constant lift-off, metals can be accurately identified by their conductivity and/or permeability
- *defect detection* – with constant lift-off for a given workpiece, defects such as cracks, inclusions and pores have significantly different dielectric behaviour and permeability.

The principal problem in using eddy current testing to inspect engineering structures relates to the rough material surfaces; as a result, the lift-off always remains a variable.

The method has other capabilities which, if they can be developed, would be valuable in underwater testing. Laboratory tests have shown that eddy current techniques can be used for crack depth measurement and crack tip location (ie the establishment of crack orientation angles). Whether or not they are commercially exploited depends on market demand.

7.2.9 Alternating current potential drop method

When an alternating current flows in a conductor the associated varying magnetic field confines the current to a layer near to the surface (see Figure 7.4). This phenomenon is known as the skin effect, and forms the basis of the ACPD method of measuring crack depth. Suppose a current of constant strength, I, is passed through the component and electrodes at a fixed spacing, l, are used to measure the potential, V_0, adjacent to the crack and across the crack, V_1. By assuming that current flow is confined to the surfaces of the component and the crack, and that the potential drop is proportional to the current path length, crack depth, d, can be calculated from simple geometrical considerations:

$$d = l\left(\frac{V_1}{V_0} - 1\right)$$

Commercial instrumentation falls into two categories, both employing the same principle of operation but with different current and frequency parameters:

- In the first category are ACPD instruments based on a low amplitude, high frequency current source (typically 1–10 A, 5–10 kHz). In use, separate measurements must be made of the two voltages, V_0 and V_1, and the crack depth is computed manually.
- The second category uses a standard impressed current MPI source delivering 300–100 A at a frequency of 50Hz to create the potential distribution. Four probe contacts allow simultaneous measurement of three potentials, V_{0A}, V_{0B} and V_1. V_{0A} and V_{0B} are the potentials measured to each side of the crack, and are averaged. A microprocessor calculates crack depth and this is displayed directly.

Although the ACPD technique has been in existence for many years its use on land or under water is not widespread. This is partly because it can only be used for sizing surface-breaking defects and partly because older instrumentation gave unstable readings. Equipment introduced during the last few years has led to improved accuracy above water, and theoretical and experimental studies are continuing to assist in the interpretation of ACPD results.

Under water, the diver positions the potential probe with the contacts straddling a crack which has previously been located by MPI (see Section 7.2.4). The current is passed through the structure at right angles to the crack via magnetic contacts or prods. Depending on the instrument, either one or two measurements are required at that particular location and the result is relayed to the topsides operator via either a repeater station or through the communications link.

MPI and ACPD techniques are, in practice, mutually supporting. Ideally, MPI crack indications should be visible when the diver carries out the ACPD sizing so that the probe contacts straddle the mid-portion of the crack, and MPI carried out immediately prior to sizing generally leaves an adequate concentration of fluorescent particles which can be seen under ultraviolet illumination. It is also important for interpretation purposes that the topsides engineer knows the surface length of the crack, since a correction to the ACPD reading may have to be applied if the observed crack depth exceeds approximately 20% of the crack surface length. This is to take into account the effect of current passing around the ends of the crack, thereby reducing the value of V_1. A photographic record of MPI indications thus plays a vital part in the interpretation of ACPD results.

7.2.10 Photogrammetry

Photogrammetry is a well-established survey technique for land use, and has now gained acceptance as an underwater survey technique, having first been used commercially in the North Sea in 1979.

The principle of stereo-photogrammetry is that the point(s) to be measured are photographed from two different positions so that each object point is imaged in a different position on each film. By measuring the position of the image on each film the position of the object point can be calculated relative to the positions of the camera(s). Camera calibration gives the optical geometry and distortion characteristics of the lens and any lens distortion can effectively be removed by computer analysis.

When applied under water, photogrammetry has generally been carried out using a pair of cameras mounted on a separation frame, although single-camera techniques do exist and have been used. Applications have been varied, and include depth measurement of corrosion pits, measurement of weld and dent profiles and mapping of complete node geometries.

Since many hundreds of points may be plotted from a single pair of photographic images, there are many methods of presenting the measured dimensions. Dimensions, cross-sections, contour maps and two-dimensional engineering drawings are all possible. CAD drawing packages also allow quite elegant isometric projections to be drawn.

When photogrammetry was first introduced for underwater use, it was used only for specific applications, but a school of thought quickly developed which proposed the use of camera systems capable of photogrammetry for all photographic work. The intention was that photogrammetric analysis could then be carried out at a later date should dimensions be required. This logic finds continued support, and many medium and large ROVs carry stereo-cameras as standard.

Two practical points to be borne in mind in any underwater photogrammetric work are:

- although photogrammetry can be used to measure the distance between two points to a high degree of accuracy, it must be possible to see both points on both films
- marine growth, poor lighting or poor stereo coverage all reduce the accuracy of the final result since they may require the observer to estimate rather than see the position to be measured.

7.2.11 Future developments

In general, future developments of underwater inspection techniques are likely to be extensions and refinements of the methods described in earlier sections here. However, there are some techniques currently at a relatively early stage of development which may eventually become available for underwater applications. They include:

- *Radiographic tomography*
  Using tomographic principles, the intensity of radiographic backscatter from a defined plane within a three-dimentional body can be analysed to differentiate between metal and air. In this way, erosion on the internal surface of a riser could be mapped.
- *Robotics and automation*
  Although computer-based techniques are used for the analysis of the output from many NDT devices, there is further scope for computerisation at the 'doing end', eg through automatic underwater machinery with teach-and-learn capabilities.
- *Neutron backscatter*
  A new method has recently become available for the detection of flooding in hollow members, based on neutron backscatter. A neutron isotope and a radiation detector system are placed together in one unit which is located against the member wall. Measurements based on neutron backscatter or N-γ interactions can distinguish between a flooded and unflooded tubular.
- *Thermography*
  Infra-red scanners are used on land to produce maps of infra-red emissions from a target area. The principle has potential to be used under water to inspect risers for internal erosion of wall thickness. Areas of reduced wall thickness in a riser carrying crude oil at a temperature higher than the surrounding sea water will show up as 'hot spots' on a map of isotherms. It should be possible to map temperature differences as small as 0.2°C. As sea water rapidly absorbs infra-red energy, it would be necessary to locate the infra-red scanner in a small dry habitat attached to the riser surface.
- *Holography*
  This is a technique for reproducing a stereoscopic image without cameras or lenses. A monochromatic, coherent, and highly collimated beam of light from a laser is separated into two beams, one of which is directed to a high resolution photographic plate. The second hits the subject and is diffracted to the photographic plate where a hologram is formed – by the combined effect of the phase and amplitude of the two beams. The hologram is an interference pattern rather than a collection of light and dark areas as with a conventional photographic negative. The original subject may be recreated by placing the hologram in a beam of coherent light (generally from the same laser) where it behaves as a diffraction grating, producing two beams of diffracted light – one giving a real image, and the other a stereoscopic virtual image so that a change of viewing position gives a different perspective of the original subject. There are suggestions that research into applying these principles to underwater inspection may be in progress and also that research may also be under way into developing a holographic diffraction technique using acoustic energy.

Table 7.2: *Advantages and limitations of visual inspection techniques*

Advantages	Limitations
Human eye	
Colour capability	Requires human presence
Depth (3-D) perception	No permanent record
Access to significant memory	No inbuilt image-enlargement capability
Access to some computing power	No remote or third-party viewing
No instrumentation to purchase, carry or maintain	Not always objective
No external power-source requirements	Recognition limited by past knowledge and experience
Usually high reliability	
Intrinsically safe	
Still photography	
Higher resolution than CCTV	Artificial lighting always necessary
Full colour rendering	Time delay before results available
Relatively inexpensive	No real-time records
Relatively low skill requirements	No remote or third-party viewing in real time
Permanent, reproducible images	Some difficulties in interpretation (particularly in black and white)
Magnification of images	
Data recording onto images relatively easy and economic	
3-D images possible and relatively inexpensive	
Video (CCTV)	
Real-time movement may be seen and recorded	Poorer resolution than photography
Full colour rendering	Some difficulty in interpretation (particularly in black and white)
Remote viewing by many	Artificial lighting sometimes necessary
Magnification of images	Radio interference (unless all equipment in good condition)
Operates in very low light levels	
Instant results (no waiting for processing)	
Camera size reductions likely in the near future	

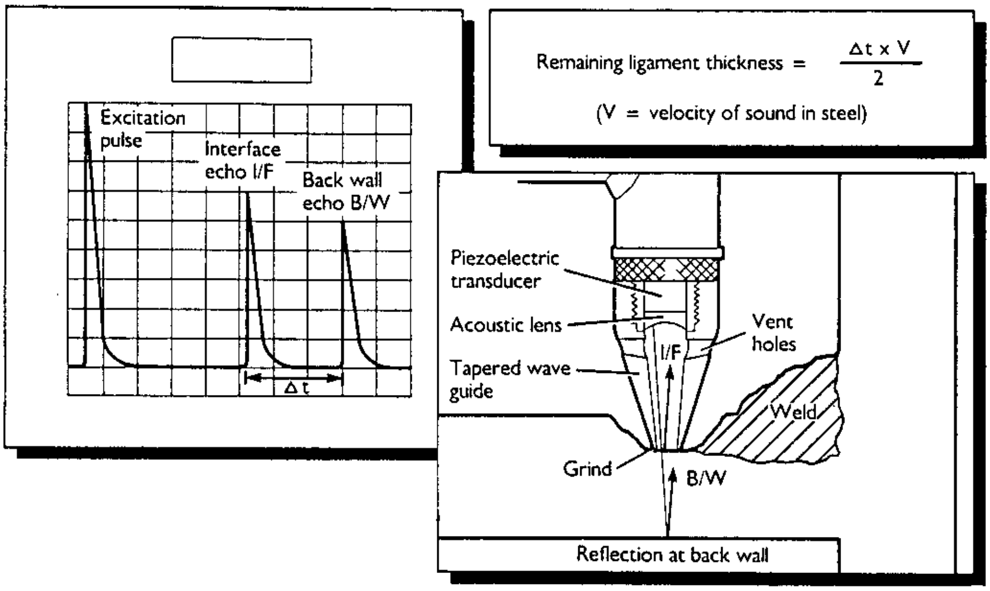


Figure 7.1: *Operation of ultrasonic equipment for measuring remaining ligament thickness after grinding (or depth of corrosion pits)*

(Courtesy of British Gas Engineering Research Station)

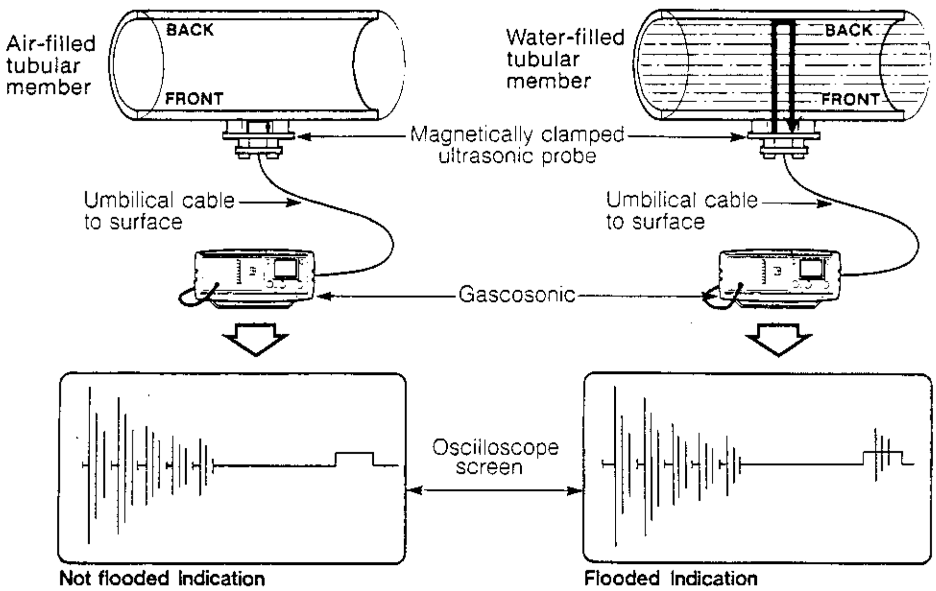


Figure 7.2: *The principle of ultrasonic flooded member detection and typical screen displays*

(Courtesy of British Gas Engineering Research Station)

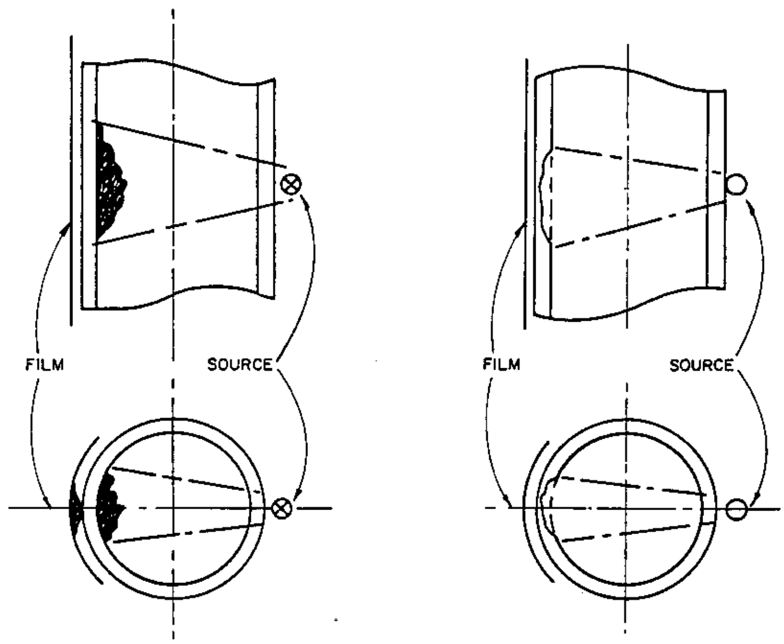


Figure 7.3: *Radiographic source and film layout to detect internal corrosion or blockage of an underwater pipe*

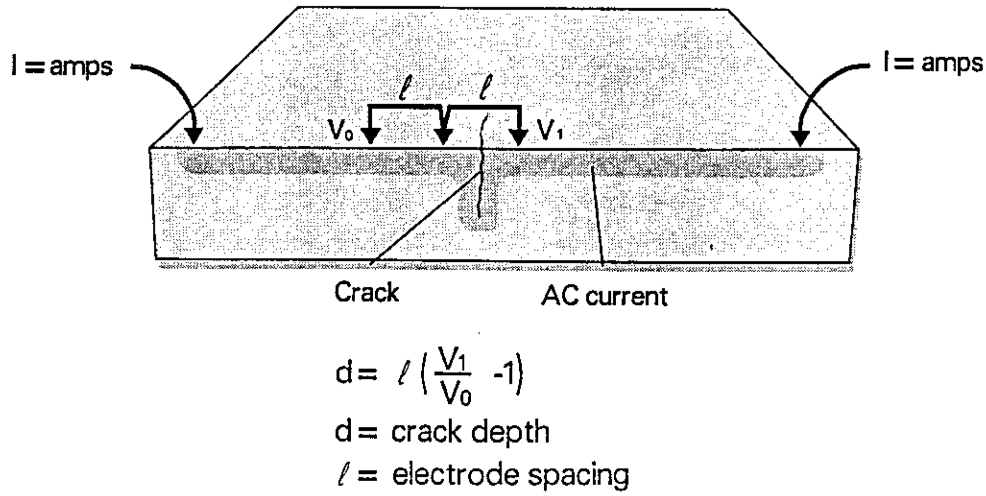


Figure 7.4: *Principle of operation of the ACPD method for measuring crack depths (Courtesy of British Gas Engineering Research Station)*

7.3 CLEANING METHODS

Most of the cleaning work carried out in the North Sea on underwater installations is part of the preparation necessary before close visual inspection or non-destructive testing (see Section 7.2) are carried out. The methods used range from those that are slow and simple using inexpensive tools to fast, complex methods using expensive equipment.

7.3.1 Brushes and grinders

Simple hand tools such as wire brushes and scrapers have their place in underwater cleaning operations. Even when high technology methods are used they have a useful supplementary role by enabling small localised finishing touches to be made as required.

There are a number of machines on the market which use pneumatically or hydraulically powered rotary nylon or steel brushes or cutters to remove marine growth. The machines are either hand-held or ROV operated and rely on the rotating action of the brushes or cutters to create a suction which holds the machine onto the member to be cleaned. Brush machines need several changes of head (usually three) from stiff and coarse to fine bristles before they achieve a satisfactory surface finish; cutting machines clean off marine growth without changing the cutter. The surface finishes achieved with brushes and grinders are rougher than those obtained from high pressure water jetting (see below), and surface damage to paint work or welds may occur. Cleaning rates for this type of machine vary between 5 and 50m^2 per hour.

Chipping hammers and needle guns are rarely used today, as their repeated hammering may cause damage through peening and deformation of the metal surface, especially at the edges of any cracks that may lay in the area being cleaned.

Grinders are frequently used in conjunction with magnetic particle inspection methods, to determine whether MPI indications are spurious and unimportant or actual cracks (see Section 7.2.4).

7.3.2 High pressure water jetting

High pressure water jetting techniques use the impact force of a water jet to remove marine growth, scale and rust from submerged surfaces prior to NDT work. The basic equipment used under water comprises a lance attached to a pump via a length of high-pressure hose. The lance is reactionless – the jet thrust is balanced by a coresponding retro-jet – thus enabling the diver or ROV operating the lance to maintain position. The pump must be large enough to supply the jet, the retro-jet and overcome power losses in transmission. Cleaning rates and performance are affected by:

- operator training, skill and fatigue
- underwater visibility
- type of marine growth and other surface deposits
- the required surface finish
- jet pressure, nozzle diameter, stand-off distance and incident angle.

The most frequent cause of downtime is failure or entanglement of the high-pressure hose.

Most of the widely available conventional water jetting equipment operates at pressures up to 120 N/mm^2 (17,000 lb/in^2) and cleaning rates of between 8 and 30 m^2 per hour can be achieved for the removal of marine growth. A better surface finish (to Sa 2.5) and higher cleaning rates can be achieved by introducing abrasives into the water jet (see below), although this is not normally necessary for fouling removal. Equipment operating at pressures up to 350 N/mm^2 (50,000 lb/in^2) is used but it has been reported that it is difficult to aim the very fine jet characteristic of this type of cleaner at small areas of residual hard growth particularly in water with disturbed currents.

Cavitation jets are also used. The underlying principle of cavitation involves stimulating the growth of undissolved gas nuclei to form low pressure bubbles in the water within the jet nozzle. The bubbles collapse at the surface to be cleaned, creating very high stresses over many small areas. This localised amplification of pressure provides the cleaning action. Two or three different systems of this type are available in the US; one uses water pressures of approximately 120 N/mm^2 and another only 25 N/mm^2. According to reports, the lower-pressure system appears to be as effective as the much more expensive high-pressure one. European equipment manufacturers have suggested that an acutely sensitive 'depth-offocus' characteristic prevents effective underwater use of the cavitation principle but there are a number of other reports contradicting this suggestion.

The introduction of abrasive solids into water jets has proved extremely effective in reducing underwater cleaning costs. Equipment costs are reduced (water pressures of 7–30 N/mm^2 are sufficient) and work rates are increased. The abrasives used include sand, grit, metal slag, crushed fruit seeds and crushed ice. Recently, air-entrained grit with a low pressure water jet has proved effective with some operators to a depth of 40 m. Further developments of this technique are being considered for use at greater depths.

In the systems used commercially at present, the solids are introduced as a slurry although, theoretically, solids maintained dry until the venturi should give the best results. Whether the solids are dry or wet, space must always be found on deck for large volumes of bagged material and pre-planning must ensure sufficient stocks are always available when required.

Fears have occasionally been expressed that entrained abrasives may remove metal from surfaces as well as any fouling, rust, etc. However, studies and trials indicate that there is virtually no risk from a single cleaning and there is minimal risk from repeated cleanings over the lifetime of a structure (providing the correct nozzle/jet is used). There is also a risk that edges of defects will be peened by the abrasive, so degrading MPI test results, but investigations have shown that this effect is only likely to be relevant for very shallow cracks (of the order of 2 mm or less).

These are some advantages to using ice as the entrained solid. It was first used offshore in 1983 (not in the North Sea) and has been entirely successful at depths down to 150 m. The ice is continuously made and crushed as required. The principal advantages of using ice are:

- no offshore storage space is required for the abrasive solid
- the solid does not have to be ordered from stock before use
- there is no apparent metal abrasion on the surface
- there is no apparent peening of defects.

7.3.3 Clean and paint machines

Automated clean and paint machines are a recent development prompted by the need to reduce the use of divers. Two systems are available on the UK market, both designed for use solely on tubular members. A hydraulically powered carriage is clamped onto the member and is remotely controlled by guide wires from the surface or from an ROV. It carries nozzles for high pressure water jetting (with or without abrasives) and for airless paint spraying. The unit travels along the member to be cleaned; it cannot clean nodes and anodes and must be disengaged by divers or ROV and moved around these obstructions.

7.3.4 Relative performances

It is unlikely that cleaning rates of more than 10–15 m^2 per hour can be achieved in removing fouling by the use of high pressure water jetting equipment. Higher rates claimed by some manufacturers have been obtained in trials on small areas or on large and easily accessible ships hulls. Most manufacturers claim that their water jets can be used from ROV manipulator arms but, because of problems associated with maintaining position during jetting, cleaning rates from ROVs are likely to be substantially less than 10–15 m^2 per hour.

Automatic clean and paint machines are clamped in situ and do not require reactionless water jet guns. There is, therefore, a more efficient use of pressure from the pump so that higher pressures can be employed during cleaning. Hard marine growth can be removed at rates up to 25 m^2 per hour in practice. Whilst these rates are significantly better than water jets, they do not include time spent in positioning the machine or in moving it around obstructions.

The highest rates of marine growth removal by rotary brushes and cutters during a prolonged offshore test have been up to 30 m^2 per hour for a diver-operated tool. Rates of up to 1000 m^2 per hour have been quoted, but these are based on small-scale tests. Rates of cleaning from ROV-mounted rotary cutters would be less than those with diver-held tools because of the problems of maintaining station. The surface finish with rotary cutters is not as good as that obtained with other methods of cleaning.

The choice of method to be used should be made on the basis of maximum cost effectiveness. The overall cost of cleaning is related to the speed at which a specified standard of cleanliness can be achieved and the dayrate costs of hiring the necessary equipment. Day rate costs are directly related to the pressure rating of equipment used (for the water jetting methods described above) but the fastest cleaning rates are not necessarily achieved with the highest pressure equipment. The 'brawn' of high pressure is no substitute for the 'brain' of a fully optimised cleaning method with, for example, an abrasive entrained in the water.

7.4 INTERVENTION METHODS

Four methods of getting equipment and personnel to an underwater inspection site are described in this section, concentrating on how the methods affect and limit the inspection work itself. The reader should make reference to other publications(eg 7.3 and 7.4) for fuller descriptions of the methods.

7.4.1 Diving

Table 7.3 summarises the different diving methods used for underwater inspection work.

In surface-orientated diving, the diver's breathing gas is supplied directly from the surface through a hose in the umbilical connection which permanently links the diver with his surface support equipment and personnel. The umbilical also contains a two-way communications link, allowing conversations between topside and the diver so that the diver can continuously report back to the surface. The diver enters the water in a basket or stage, in a 'wet' bell (at ambient pressure) or via a ladder from the installation deck. He usually carries out his decompression in a deck compression chamber (DCC), not in the water. In UK waters, this method of diving is limited to depths of 50 m.

At greater depths, divers do not work directly from the surface. It is necessary to use a pressure vessel (a diving bell) to transport them from the surface to the worksite. When they reach the worksite, they can first make an inspection at atmospheric pressure in the relatively dry and comfortable conditions of the bell. After pressurising, they leave the bell to work in the water but they always remain attached to the bell by umbilical connections. The divers are dressed generally as for surface-orientated diving although a heated suit is normally worn. The usual breathing gas for this method of diving is a helium/oxygen mixture (heliox), although nitrogen/oxygen mixtures or air can be used if bell diving is carried out at depths of less than 50 m. After working, the divers return to the surface in the bell but still under pressure. Decompression takes place in a DCC on the surface.

Overall, bell diving requires considerably more plant and equipment on the surface than other forms of diving (see Figures 7.5 and 7.6).

Bell diving can be carried out using 'bounce' or 'saturation' techniques. A diver reaches saturation when his body tissue and blood can absorb no more gas from his lungs. He can be maintained at pressure for long periods under saturation – his decompression time is the same no matter how long he remains saturated – and there is no need for him to decompress to atmospheric pressure at the end of each working shift. In bounce diving, the diver is exposed to pressure for insufficient time to become saturated; he works for a short period (typically less than 30 minutes) and is then decompressed back to surface pressure.

SCUBA (self-contained underwater breathing apparatus) diving is virtually never used for the inspection of underwater installations.

Each diving method has its limitations:

- *Legislation and guidance*
  Diving companies must conform to any statutory regulations that apply to diving operations in the country in which they work. Generally they also conform to agreed industry and governmental guidelines, and these form the basis of most company operating procedures and specifications. A selection of relevant legislation and guidance is listed in the Bibliography. The regulations and guidance may affect the choice of diving method for a particular inspection task:
  - by limiting the depth at which surface-orientated diving must be replaced by the more expensive bell diving.
  - by restricting the length of umbilical that can be carried or handled effectively, thereby reducing the distance that a diver can travel through a structure.
  - by fixing the endurance of divers' bail-out (emergency) gas bottles.
- *Physical and physiological limitations*
  A diver under water is in an unnatural state and, inevitably, much of his concentration and effort must be directed towards staying alive. Some of the hazards are:
  - Nitrogen narcosis – the effect of intoxication brought about by breathing nitrogen at high partial pressure. A diver suffering from this condition may have difficulty in interpreting results of tests, in ensuring that tests are performed at the correct locations and in the specified manner, and in responding effectively to instructions from the surface.

- High pressure nervous syndrome – a general excitation of the diver's nervous system, dependent on the compression rate and absolute pressure. Symptoms can occur at depths as shallow as 90 m but slow compression rates and acclimatisation periods now make diving viable to about 300 m with development work presently underway to extend this to 450 m. The symptoms which would affect inspection task performance, such as hand tremor, can be overcome by concentration but the effort needed to overcome the syndrome can rapidly lead to excessive fatigue.
- Cold – which limits the diver's ability to accomplish inspection tasks. The initial effect is loss of sensation in the extremeties and loss of fine manipulative capability. Further chilling results in reduced mental capabilities but a dive would be terminated before that level was reached. The necessary use of protective clothing and equipment to prevent chilling increases the diver's bulk (which reduces his mobility), increases the size of his umbilical (increasing both its drag and stiffness), and necessitates the use of gloves (reducing both dexterity and the sense of 'touch').
- Helium speech – the distortion of speech when breathing helium-oxygen gas mixtures. The effect becomes worse as the diver works at deeper depths. Even using a 'helium unscrambler' to make speech intelligible, messages can be impaired by distortions caused by breathing noise, breathing apparatus noise and environmental noises.
- Noise – from water-jet blasters, grinders, wire brushes, etc. Equipment noise can make it very difficult for the diver even to be aware that surface supervisors are trying to attract his attention. Noise has been known to reach levels that endanger diver health and well-being (ie cause temporary or permanent deafness, disorientation, etc).
- Decompression sickness – caused when the diver is returned from ambient pressure to surface pressure too quickly. The need for controlled decompression limits the amount of working time available to a surface-orientated or bounce diver, and restricts the amount of vertical travel that a saturation diver may make (without further compression or decompression).

- *Equipment*
The life support equipment that a diver must carry encumbers his movements. The bulk, particularly of his mask or helmet and his back-mounted emergency bail-out bottle, may keep him just too far away from being able to reach an inspection item within a confined area. Hand coverings limit his ability to feel and to make fine manipulations. Drag on his umbilical in a current leads to increased energy expenditure and may rapidly cause fatigue with its associated reduction in performance.
The inspection equipment itself can create further problems. In the past (and still today in some areas of the world) underwater inspection equipment has been nothing other that 'marinised' land equipment, with problems of technical inadequacy, unmanageable bulk, shape, and weight, and unsatisfactory electrical connections. These problems, although greatly alleviated, can still benefit from further design developments. In addition, equipment that normally is operated by two or more technicians above water may have to be used by a single man under water. This greatly slows the work progress and can lead to inaccuracies or inability to perform the task at all in extreme circumstances.
- *Environmental factors*
The sea state may make it impossible for the diver to reach his worksite by preventing an entry through the air/sea interface. If his worksite is in the surge zone itself the sea state may make work impossible (and the effects of swell can extend well below the surface).
Currents and tide may also prevent the diver from reaching the worksite or may impede his work in other ways (eg by washing away MPI particles).
Suspended solids in the water may be sufficiently dense to restrict the divers visibility and thus effect the quality of his work. He may go to the wrong worksite altogether, or find it difficult to record his results or to see the full extent of damage.
Pollutants from oil, drilling cuttings or hyperbaric welding gases can cause problems.
Prolonged exposure to low water temperatures can seriously affect a diver's performance (see 'Physical and physiological limitations' above).

7.4.2 Atmospheric diving suits

An atmospheric diving suit (an ADS) is a pressure vessel where the operator inserts his arms inside articulated extensions to the vessel. The operator is able to actuate grab and rotary-type grippers from inside the arms. ADSs can work down to depths of 700 m, with communications (and sometimes power) supplied via an umbilical connection with the surface. A fundamental feature of all ADSs is that the operator works at a pressure of one atmosphere – there is no requirement for decompression after working.

A bottom-orientated ADS has articulated extensions for the operator's legs as well as his arms, so that he can walk on the sea bed or any horizontal surface. 'Swimming' is not possible but the operator is able to exert large and finely controlled force with his arm extensions. ADSs of this type are therefore best suited for drilling and construction work, not inspection.

A mid-water ADS has no leg extensions but relies on thrusters for movement through the water. It is highly mobile and especially suitable for tasks like visual inspection where large areas are to be covered. Unless fitted with a clamping mechanism, it has difficulty in remaining in a fixed position and of exerting a finely controlled force. It may not work well near the sea bed, where the thrusters may stir up sediment and reduce visibility, or in areas where seaweed, ropes and other debris may foul the thrusters. Two examples are shown in Figure 7.7.

Whichever type of ADS is used under water, a considerable quantity of plant and equipment must be available above water. The amount is less than required for bell diving but includes:

- a primary main hoist winch
- a secondary hoist winch
- a guidewire/shot line winch
- a control cabin
- a handling system
- two high pressure air compressors
- an oxygen transfer pump
- oxygen banks
- air banks.

In addition, equipment (and a contingency plan) must be available for rescue of the ADS operator in an emergency.

Although ADSs avoid the need for diver decompression, there are limitations to their usefulness:

- *Legislation, etc*
  As with ambient-pressure diving, statutory requirements and non-statutory guidance control and limit operations (see the Bibliography).
- *Physical and physiological limitations*
  ADSs do not normally have any means of internal temperature control. If the operator is not dressed for seabed conditions and becomes too hot or too cold, he will perform less efficiently and the dive may have to be aborted.
  'Flying' or 'hovering' a mid-water ADS (or 'walking' a bottom-orientated ADS) make physical and mental demands on the operator which can cause serious fatigue and reduce the operator's ability to perform his tasks. This can have quite significant detrimental effects, particularly in inspection operations. If the operator can attach the ADS to the structure during detailed inspections, the need for continuous flying is removed.
  An ADS is a closed-circuit system, limited in its ability to remain under water by the extent of on-board supplies of oxygen and carbon dioxide absorbants. Dive duration cannot exceed the designated time limit (emergency supplies carried must not be used merely to extend the working time of a particular dive).
- *Equipment*
  The bulk of an ADS is substantially greater than the bulk of a diver even in a thermally protective suit. Thus the ADS operator's eyes (and hands) are displaced further from an inspection site than a diver's eyes. His ability to examine items closely and distinguish fine detail are reduced. The bulk of the suit and its limited articulation limit the areas that the operator can reach. Deployment into the interior of a jacket structure also risks entrapment or umbilical entanglement.
  At any location, an ADS operator has poorer sensory feedback than a diver – he must

depend on sight only to judge his movement through the water (and is therefore at very considerable disadvantage when visibility is poor). His 'gripper arms' are likely to offer limited feedback and delicate touch (although they may be able to offer more-than-human force and torque).
An ADS is further limited in inspection operations because most inspection equipment has been designed with the human hand in mind, not gripper-type manipulators. Even simple photography/videography may be difficult.

- *Environmental factors*
  As a general rule, ADSs are more affected by underwater currents than ambient-pressure divers are and less affected by sea state than are surface-orientated divers. A current of 1 knot (or even 0.5 knot for mid-water ADS) or a sea state of 5 on the Beaufort Scale is likely to make ADS operations impossible although, of course, the ADS diving supervisor may choose to cease operations at lower limits than these. More recently manufactured suits may have better environmental capabilities.

7.4.3 Manned submersibles

Manned submersibles and ADSs (see above) share many characteristics and limitations as far as underwater inspection is concerned. Only the differences are highlighted here. The main differences are that submersibles are not anthropomorphic and are usually (but not always) designed for a crew of two men. They also rarely have an umbilical connection to the surface – the exceptions being thrusted and mobile bells, which are hybrids sharing some of the characteristics of diving bells (see Section 7.4.1) and manned submersibles.

The difference between a submersible and a submarine is that a submarine is as independent of offshore support as any other ship but a submersible is dependent on a 'mother ship' fitted with a considerable quantity of equipment for launch and retrieval and for replenishing the submersible's power supplies. Submarines have not been used for commercial offshore work at all. In fact, submersibles have also been little used in recent years; they have been almost universally replaced by ROVs (see Section 7.4.4 below).

Submersibles can be used:

- As observation vehicles so that, for example, an oil company engineer can inspect underwater installations himself with relative ease and safety. They can also carry still and video cameras.
- As platforms for manipulators so that work can be done externally. In the past, electric- or hydraulic-powered manipulators have usually been used for construction work such as cutting and bolt tightening, not for inspection activities,. Where suitable manipulators are available and the submersible can gain access and 'park', the submersible could be used for inspection work.
- For diver lock-out where, in addition to the atmospheric chamber, the submersible has a second, pressurised, compartment from which divers can operate. In this way the submersible can extend its activities into areas where the craft itself cannot penetrate.

The limitations on submersible use are generally very similar to ADS limitations (although, of course, the factors affecting lock-out diving operations are similar to other diving limitations):

- as the submersible does not usually have an umbilical, most operations are limited by the battery capacity of the submersible, and the main drain on the batteries is use of the thrusters
- a submersible is even more bulky than an ADS and an inspector on board will always be at least one metre away from the inspection site
- the submersible can be expected to carry (in an external 'basket') more inspection equipment than divers operating from a bell but it can only be accessed by manipulator equipment
- a submersible can only work satisfactorily if it is fixed in position at the worksite, but no mid-water structural attachment methods yet devised have been completely successful
- lock-out diving is unsafe while a submersible is hovering
- for safety reasons, a submersible is not normally permitted to enter the lattice of a jacket structure.

Observation and manipulator submersibles can operate at depths down to 1000 m and in currents up to 2.5 knots with underwater visibility of 5 m.

7.4.4 Remotely operated vehicles

Safety considerations and the high cost of putting man into the water – as a diver, in an ADS or in a manned submersible – have contributed to the development of the unmanned submersibles that are usually known as ROVs (remotely operated vehicles).

Most ROVs in use today are tethered vehicles controlled by a pilot at the surface, either small observation vehicles or larger working vehicles. The vehicles carry the equipment necessary for their work, such as lights, navigation aids, still and/or video cameras, and possibly one or more manipulators. They have their own means of propulsion (thrusters), receiving power from a support vessel via the umbilical connection.

The observation vehicles are often referred to as 'flying eyeballs' and are basically a highly mobile underwater camera, although they can sometimes carry out cathodic potential readings and, increasingly today, flux density readings (see Section 7.2.2). These vehicles are invaluable in assessing general structural condition, detecting gross damage, debris and marine fouling, and in assessing the condition of anodes, paint and riser clamps. Although the vehicle keeps a man out of the water, a diver often follows up to collect more detailed information and measurements. Another very beneficial use of eyeballs ROVs is as support to diver operations. Some operators insist that divers and their work are continually observed remotely through an ROV video. Section 7.2.1 contains a discussion of the relative benefits of divers and ROVs for visual inspection purposes.

Tethered ROVs with working capability are generally larger than eyeball ROVs in order to support the necessary external tools and equipment. They are normally fitted with single or dual manipulators. When used for manipulative inspection tasks it is also advantageous for the ROV to be able to attach itself temporarily to the structure on which it is working. Up to now, working ROVs have been mainly used in support of deepwater drilling operations, underwater maintenance and pipeline inspection. Their use for detailed platform inspection has been limited by the problems of remote cleaning and the as-yet unresolved problems in performing remote MPI (or some other equivalent NDE method for detecting defects). And, of course, the more difficult requirement for defect sizing cannot be satisfied either. However, it should be stressed that development of working ROVs is progressing rapidly. It would not be unreasonable to expect credible and reliable remote inspection capabilities within the next few years.

Some ROVs are untethered, ie self-powered and operating without physical connection to the surface. Manoeuvrability is generally three-dimensional and collected data is stored aboard the vehicle. ROVs of this type are in use but development is presently at a very early stage. The intention is that they should operate either computer programmed or acoustic controlled. In the first case, a task is given to the vehicle's microcomputer, which directs the vehicle in terms of depth, course, speed, data to be collected and when to return. With acoustic control, movement and activity are controlled via through-water acoustic communication from the surface or via radio.

Typical ROVs are illustrated in Figures 7.8 and 7.9.

As with other forms of underwater intervention, ROVs have their limitations:

- *Legislation, etc*
  There are no statutory regulations for the use and operation of ROVs, except in relation to the operation of their motherships. However DnV have issued relevant publications on this subject and guidelines have been issued by the Marine Technology Society of America and by the Association of Offshore Diving Contractors in the UK.
- *Equipment*
  Although the bulk of an ROV may be less than that of a diver, it may have more difficulty in making access to an inspection site due to its umbilical, restricted manoeuvrability and lack of spatial awareness.
  Where the cameras on an ROV are recessed for protection, the ROV's 'eyes' are effectively further away from a worksite than a diver's would be. However, this is not the case where the cameras are mounted on a manipulator which can be moved to optimum viewing positions.
  When an ROV is equipped with manipulators, the same difficulties are experienced as with a manned submersible or ADS in using equipment designed for the human hand. In addition, the shape, bulk and weight of some inspection equipment presents an almost insurmountable problem for use by some ROVs.
  ROVs are normally designed with a slight positive buoyancy, and if the inspection

equipment is negatively buoyant the vehicle may not be able to function effectively or safely unless extra buoyancy is added. The equipment can also increase the profile of the ROV, degrading its hydrodynamics and reducing its speed and the speed of the maximum current in which it can work effectively.
Specialised electronic equipment is necessary on the ROV to transmit data back to the support vessel. Transmission through a slip-ring umbilical connection can lead to loss of signal and data and there may be interference in the umbilical itself.
It is sometimes difficult for an ROV to maintain position and at the same time exert force with an inspection device or tool. Conversely, any unexpected movement of an ROV during an inspection task can drag the inspection tool across the worksite surface, causing the tool to be damaged (the pilot's reactions at the surface are delayed – due to remoteness, lack of spatial feedback and absence of 'tactility').

- *Environmental factors*
  Environmental factors limit operation of the ROV itself and of the support ship at the surface. Operations carried out close to a platform or other installation are more severely limited than operations in open sea.
  As ROVs operate in deeper water, more attention must be paid to components sensitive to seawater pressure and to losses in the umbilical connection.
  Increasing sea states affect ROV launch/recovery operations and increase the liklihood of shock loads being transmitted through the umbilical from a heaving support ship to the ROV itself at depth. There is a risk of parting the umbilical, or pulling the ROV off its work station if it is working at relatively shallow level.
  An ROV is affected by local currents (varying with depth and caused by eddies around a structure) not just depth-averaged current. Its ability to manoeuvre in current is dependent on its depth, the length of umbilical deployed and its attitude relative to the current. The maximum current in which the ROV can work is never as great as the maximum forward speed of the vehicle.
  Good in-water visibility is essential to ROV operations, so that the pilot on the support ship receives a satisfactory video picture by which to steer the vehicle. Visibility can be degraded when an ROV is manoeuvring near a silty sea bed or carrying out operations such as removing marine growth or preparing surfaces for NDE. An experienced pilot can use any in-water currents to best advantage to minimise these effects – by positioning the ROV up current and directing any water-jet nozzles downstream and at an angle of 45 degrees to the worksite surface. He can also experiment with different light levels to get the best picture in clouded conditions. Pressure waves set up by cleaning equipment can also affect the quality of video pictures; they disturb any less-than-perfect electrical connections in the electronic circuitry.

Support equipment for ROV operations is less extensive than with other deepwater intervention methods, but the highest standards of effectiveness and reliability are essential in the equipment that is used. Operations can be mounted from either a vessel or a structure, and the basic plant and equipment required is:

- the ROV itself
- a control cabin
- an umbilical handling system
- a launch/recovery system
- equipment for underwater navigation and/or tracking.

To overcome some of the environmental limitations described above, an ROV can be used in conjunction with an underwater 'cage', 'garage' or 'launcher'. The layout is illustrated in Figure 7.10. The negatively buoyant tubular cage containing the ROV is deployed from the surface via the main umbilical. The ROV itself works from the cage connected by a shorter umbilical (although this can be up to 150 m long) which, because it floats relatively horizontal and is protected from the harsh environment of the air-sea interface, can be of lightweight construction and therefore cause less drag on the ROV.

Any ROV used for inspection work can only be, at best, as effective as the inspection tools and equipment it carries. ROV manufacturers concentrate on providing an operationally reliable vehicle equipped only with cameras and their control links and manipulators. Operators are left to add any NDE equipment as they wish. Equipment is available for fixing to ROVs for cathodic protection checking (see Section 7.2.2) and for thickness checking by ultrasonic methods (see Section 7.2.3), but the crack detection equipment currently available for ROV fitting can only detect cracks that are so gross as to be plainly visible. Nevertheless, credible methods of crack detection from ROVs are expected to be operational within the next few years.

7.4.5 Underwater navigation

The three purposes of underwater (or any other form of) navigation are:

- to find and arrive at a known location
- to determine a new location from a previously known position
- to provide a path of known points (which can be plotted and/or travelled) to show the location/path of an object extending for some distance (eg a pipeline or cable).

Five different methods can be used to satisfy these purposes. Each is discussed below.

Visual navigation

Visual navigation is used under water when in close proximity to the worksite. Its use is limited by underwater visibility which ranges from a few centimetres to a maximum in ideal conditions of about 60 m. As underwater visibility usually lies in the range of 1 to 10 m, disorientation is common. Some type of clear and obvious marking system is necessary, so that areas can be both located and re-located. These are discussed in Section 10.3.1. They can be installed during construction/installation or as retro-fit items at, for example, sites where defects have been discovered. They are always liable to become obscured by marine growth and so become ineffective but some markers have been developed which alleviate or eliminate this problem.

Unless there is some form of standard reference in use, divers and ROV pilots making navigation observations are always likely to vary in their reporting of information, especially regarding locations. Estimation of distances is particularly suspect. The ability of individuals on land is variable in this respect; underwater it is likely to be worse (partly because of the difference in refractive index between water and air).

Sonar

Sonar navigation can operate in a search mode, using echo location principles to locate objects, or in an interrogation mode where the sonar interrogates pre-placed transponders to determine locations with respect to a known co-ordinate system. It can be used in conjunction with all the intervention methods described above but is usually used by submersibles and ROVs. It is of particular use in locating items beyond the visual range or items without a marker (both with and without the assistance of a local grid reference system). It provides a means of plotting underwater features (pipelines, flowlines, debris, anchors, etc) without the need for physical measurement and, in suitable configuration, can be used for relatively high-accuracy measurement (to approximately 1 centimetre).

Some of the practical problems of sonar use are:

- Manufacturers' figures for 'transponder turnaround delay' may not be relevant for the particular conditions of use at an operational site. To overcome this, the user should include appropriate calibration tests in his procedures.
- The speed of sound through water is affected by variations in temperature, salinity and density. The speed (which is used to determine the distance of an object from the source of the sound) may therefore vary with depth and time. Periodic recalibration of the equipment is necessary, and even then positional measurements may vary on different days. The variations also cause the sound path to bend. Unless corrected, this will cause the distance between the transmitter and receiver to be overestimated.
- In a long-baseline sonar system, a ray path error may be introduced into positional measurements under some circumstances. With suitable calibration, these errors can be converged to less than 0.3 m.
- Shadow zones caused by obstructions can cause erroneous results.
- Multipathing – caused when the sonar pulse is reflected by structures, the surface, the sea bed, thermoclines, etc – can result in a transponder being interrogated several times by the initial sonar pulse. The result is confused data.
- Non-sonar noises, generated by vessels, the sea surface, fish or activity on the installation, can disrupt the sonar data if they are at the same frequency or they can mask the signals being sent or received.

Tracking

Tracking is a navigational method using a fixed path as a means of either reaching a point or following a path. Examples would be an ROV using a magnetometer to track a buried pipeline or cable, or divers using down-lines or cross-haul ropes. As with visual navigation, this group of techniques must be used in conjunction with reference points, sign posts, and/or measurements to give repeatable position/location information.

The major limitation of tracking is that there must be something specific to track in the first place.

Dead reckoning

Dead reckoning involves proceeding on an exact compass course at a set speed from a last known position. As with other navigation methods, known points are necessary to give repeatable position/location information. It is usual for this method to be used to reach the vicinity of an inspection site, before relying on visual navigation for final positioning using a pre-installed marker system (or other more accurate means of determining position).

The major limitation with dead reckoning is that accuracy is dependent on an accurate knowledge of speed through the water and of the velocity of any currents affecting the calculations.

Table 7.3: *Summary of commercial diving methods*[1]

Description	Typical access into water	Environmental limitations: Current[2] (knots)	Sea state (Beaufort)	Normal breathing gas	Compression (C) Decompression (D): (C)	(D)	Disadvantages and limitations	Advantages and benefits	Working depth range	In-water time limitations
Surface-orientated diving										
Both breathing gas and communications (and possibly heating) supplied through umbilical from surface	Ladder, basket or wet bell	1.5	4	Air, nitrox or oxy-helium	In water	In water (not working), in DCC[3] or both	Limited work time. Limited by surface weather	Controlled penetration into water. Storage space for tools/equipment. Additional emergency gas available. Continuous surface communications	Europe: air or heliox to 50 m. USA: air to 67 m heliox to 90 m	Limited by decompression tables
Bell diving – bounce										
Rapid compression in bell at work depth: lengthy decompression in DCC	Bell and moon-pool	1.5	[4]	Air, nitrox or heliox	In bell at depth	In DCC[3]	Relatively long decompression time for short work duration. Minimum of 2 divers required	Lower costs than saturation for short duration tasks	30 to 150 m approx	Up to 4 hours lock-out
Bell diving – saturation										
Diver pressurised for continuing lengthy work periods over many days, eg 28 days	Bell and moon-pool	1.5	[4]	Nitrox, trimix, or heliox	In saturation system	In saturation system	Requires full saturation 'spread'	Long, regular, and deep work possible	10 to 300 m approx	Up to 7 hours[5] lock-out

1 *The contents of this table are relevant only to inspection diving*

2 *Extreme current limitation; everday work is limited to about 0.75 knot*

3 *Deck compression chamber*

4 *Diving support vessels (DSVs) operate within the limitations of their design (monohull, catamaran or semi-submersible), and the operation of diving bells through moonpools and cursor systems greatly improves the sea-state conditions in which they can operate*

5 *Bell runs generally limited to 8 hours*

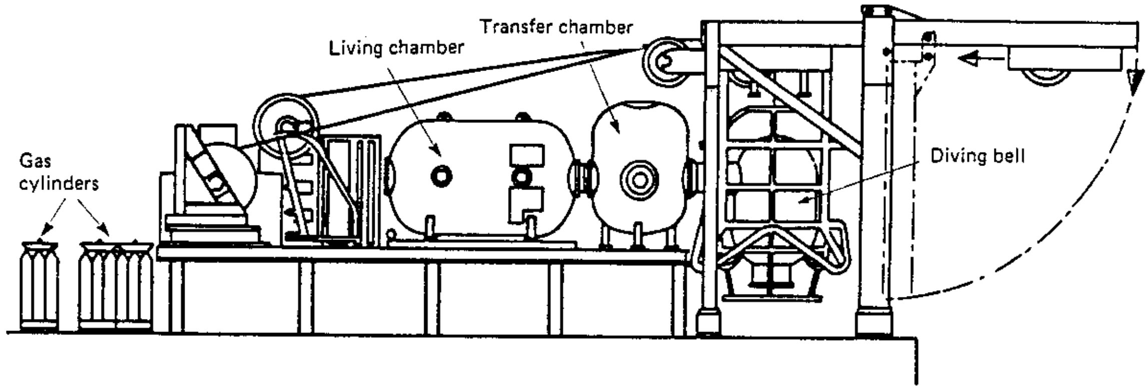


Figure 7.5: *Typical plant and equipment for bounce diving*

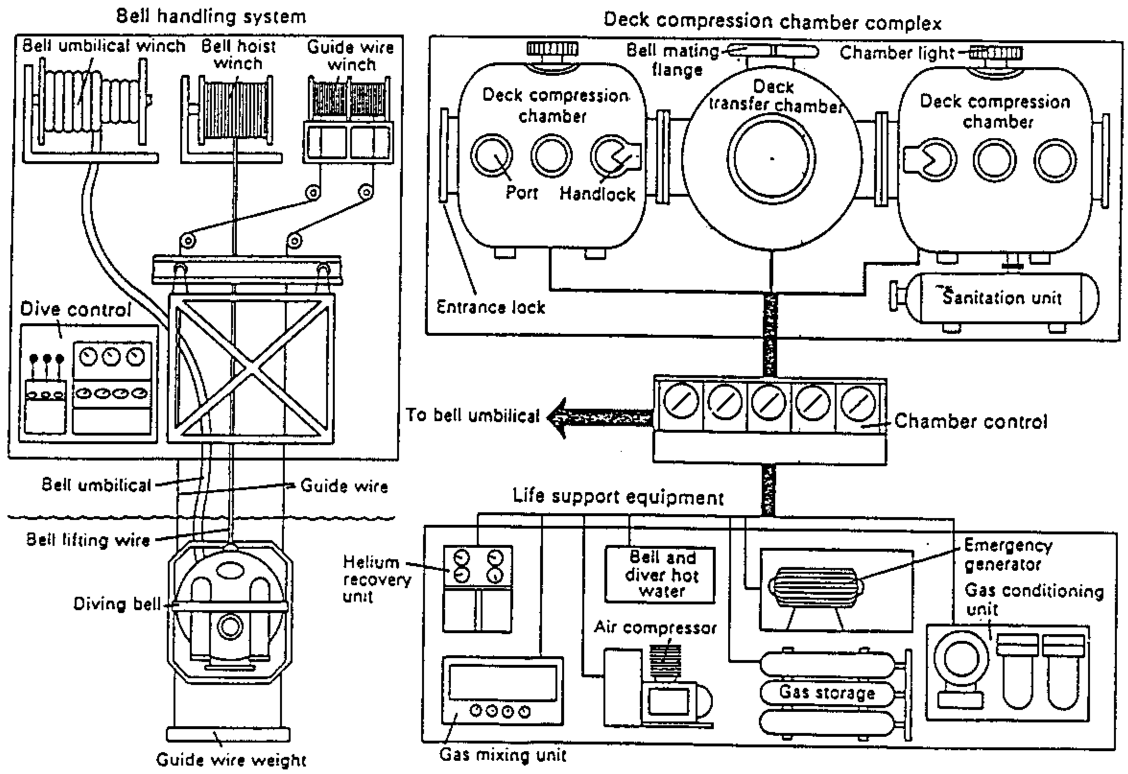


Figure 7.6: *Typical plant and equipment necessary for saturation diving*
(Courtesy of the 'Professional Diver's Handbook')

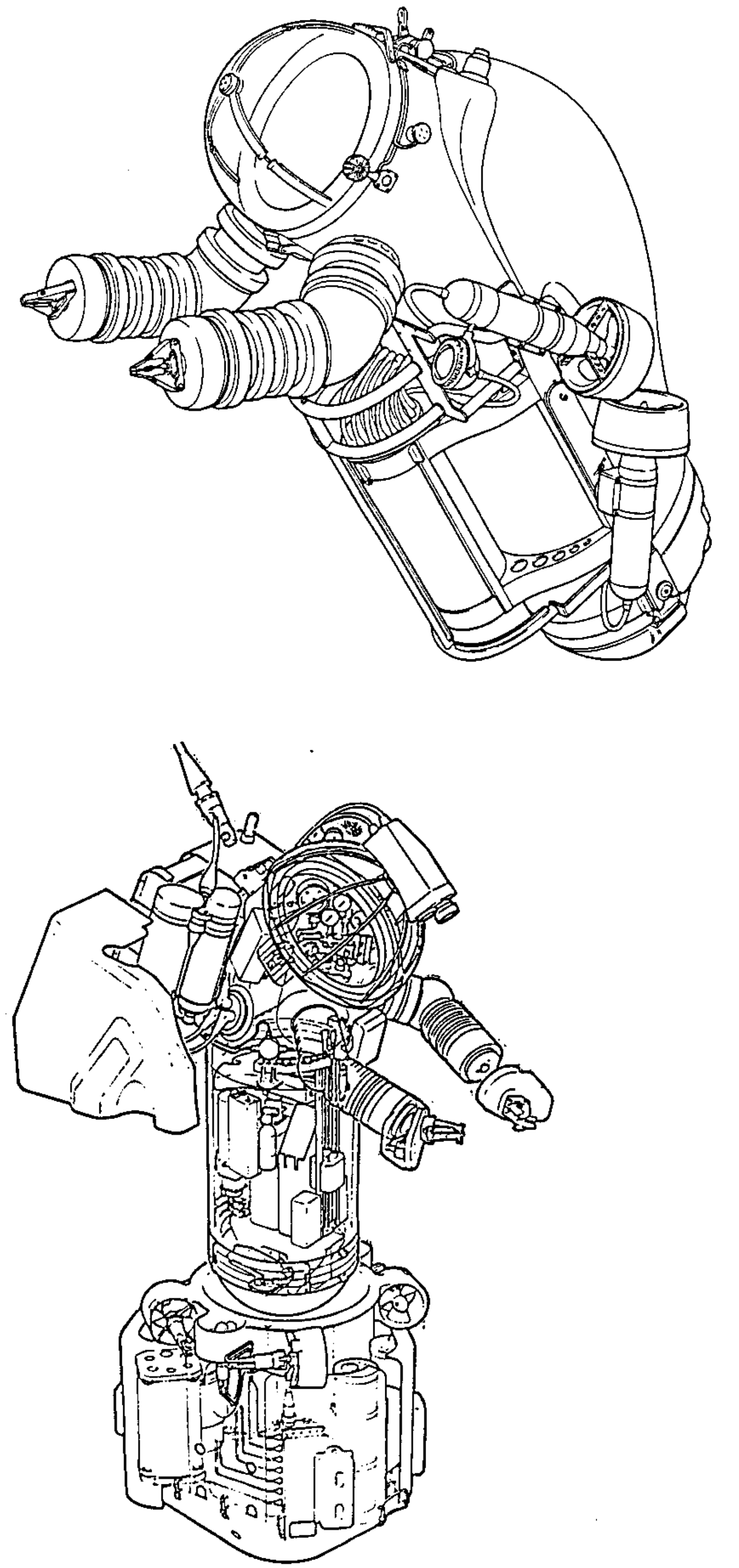


Figure 7.7: *Examples of mid-water ADSs*
('Wasp' courtesy of OSEL Group and 'Spider' courtesy of Slingsby Engineering and 2W)

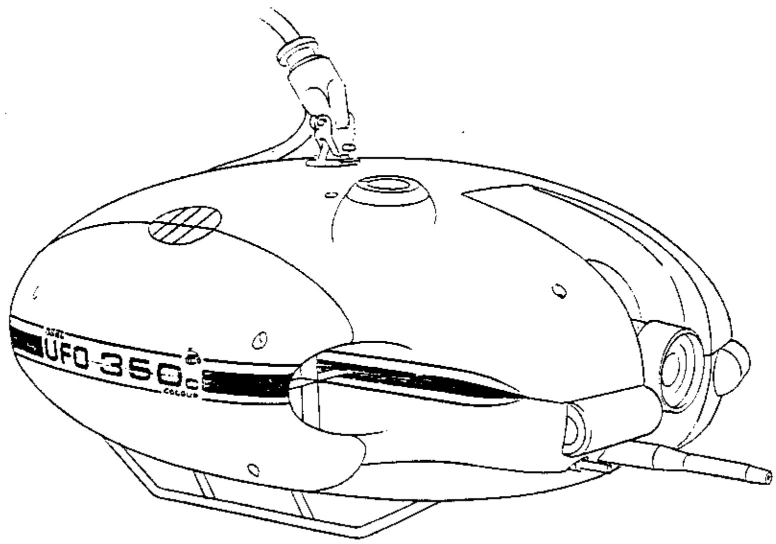


Figure 7.8: *Tethered 'eyeball' ROV*

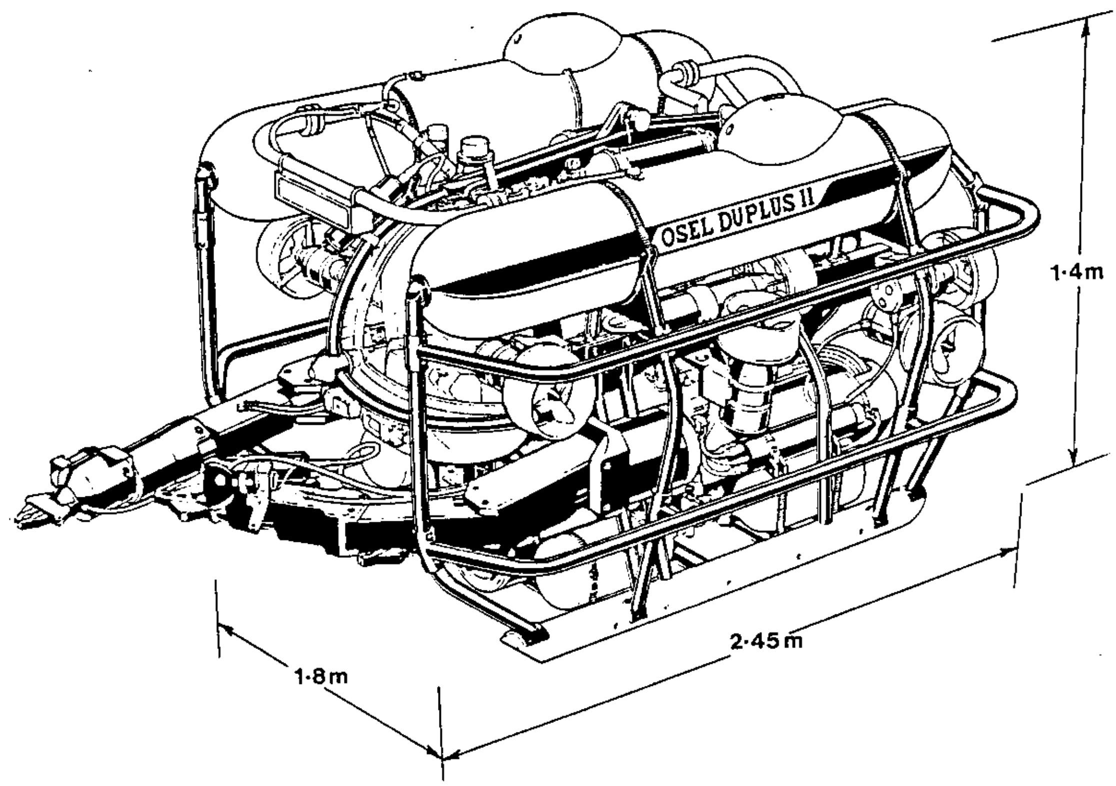


Figure 7.9: *One-atmosphere tethered one-man submersible (can also be operated as an ROV)*
(Courtesy of OSEL Group)

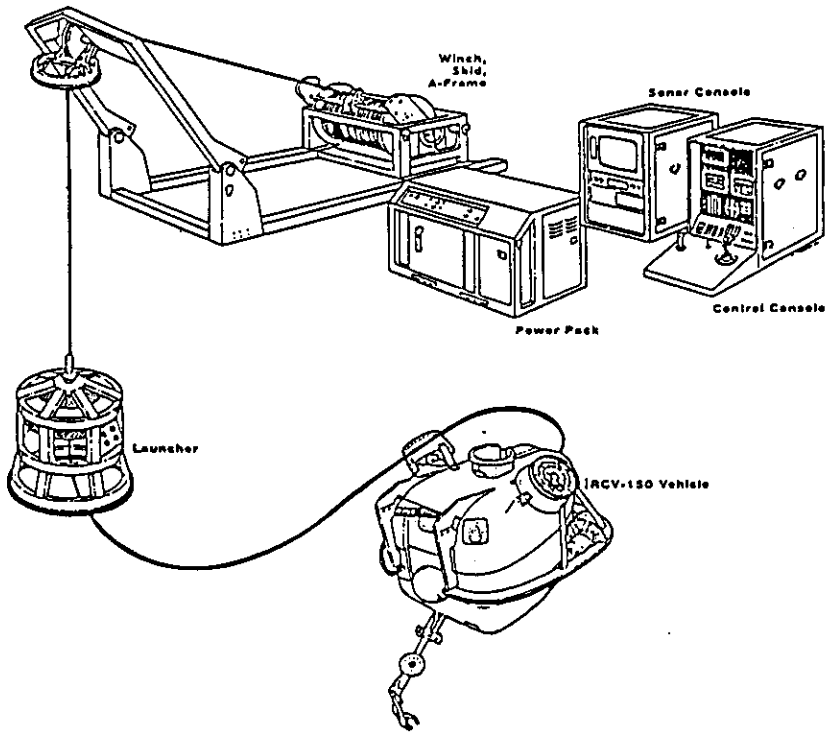


Figure 7.10: *ROV deployed from an underwater cage*

7.5 MONITORING METHODS

In this section, the components of monitoring systems are described in general and details are given of the specific monitoring systems in use. Section 7.1.4 contain a general discussion of the principles of structural monitoring and how the methods may be used in conjunction with underwater inspection.

7.5.1 Components of monitoring systems

The components of any monitoring system generally fall into three categories:

- data acquisition equipment
- data transmission equipment
- data processing, display and recording equipment.

Acquisition

Data are acquired from the structure being monitored by means of transducers (alternatively referred to as 'pick-ups', 'probes' or 'sensors'). A transducer is a device that converts energy or information from one form to another. The most commonly used transducers in offshore monitoring are based on the piezoelectric effect, which converts mechanical energy to electrical energy. Both vibration monitoring and acoustic emission transducers use this effect, produced from, for example, instantaneous displacement, velocity or acceleration.

Figure 7.11 illustrates a typical piezoelectric accelerometer.

Fitting and protecting transducers is generally seen as a potential problem area. For short-period monitoring, epoxy resin bonding or mechanical strapping have been shown to be quite effective for up to 4 years, and longer periods may be possible (although not yet actually proven). The methods used for retro-fitting transducers can be satisfactory but permanent integration during initial fabrication of the structure is usually the best approach. Attachment of transducers may not be necessary at all for some monitoring techniques – see 'through-water transmission' below. Underwater fitting and maintenance problems are also avoided with some of the vibration monitoring methods, where the transducers are placed on the platform deck rather than under water.

Transmission

A monitoring system must have a means for transmitting data from the transducers to the processing equipment. The methods currently used and under development include:

- *Cabling*
  Attached directly to the underwater structure
- *Conduited cabling*
  With the conduits attached to the structure
- *Through-water transmission*
  Self-powered devices can be used to transmit coded sonic messages from transducers, through the water to a central (underwater) control transmitter which is in turn connected to the topside by a simple cable. This concept eliminates the need for many cables running long distances. Although the demand for power at the transducers appears to present a limitation, this should be overcome by the introduction of miniature batteries, at least for short-term monitoring exercises.
  A different, though somewhat similar, method has been tested in the North Sea; it involves the centralised reception of 'raw' acoustic emissions. A cage containing a number of transducers (hydrophones) is suspended in midwater and it is claimed that it can satisfactorily receive acoustic energy created by the propagation of structural cracks.
- *Taut-wire transmission*
  Another transmission method which has recently been introduced utilises the very high strain capabilities of some modern high-stress cables (similar to those used for towing ships at sea but with signal-carrying elements incorporated). One end of the wire is securely attached at a suitable subsea point and the other end is secured above water so that the wire can be under considerable strain (hence the term 'taut-wire'). The high strain significantly alleviates the effects of wave and tide action on the wire. This method appears viable for localised monitoring but, where a global system is required with many transducers at different levels on the structure, a segregated system may be the answer. One solution could be to run a taut wire as near as possible to the structure leg, with transducer/cable penetrations from each node into the taut

wire, thus covering all nodes on the leg. More than one taut wire could be used, one per leg perhaps, thus monitoring all major nodes on the installation relatively economically.

It is accepted that data transmission components are vulnerable to damage and there is a widespread tendency to blame wave and tide action when cabling and conduiting are damaged, destroyed or washed away. However, this is not always the reason; the various attachment methods (mechanical fittings, strapping and adhesive bonding) have all been found by experience to suffer from operational activity on the platform (eg oxy-arc cutting by divers, falling objects, vessel impacts, repair activities, etc), as well as from environmental conditions.

One solution already used on at least one North Sea structure is to install a caisson within the structure to provide protection for the cabling of the monitoring system. Another is to adopt the through-water or the taut-wire transmission systems described above.

Processing, display and recording

In order to obtain the required monitoring information, transducer output signals are passed through various electronic conditioning and processing circuits, which can include amplifiers, attenuators, rectifiers, integrators and filters. The results are then displayed, on meters, plotters, visual display units, data duplication or computer systems.

7.5.2 Vibration monitoring methods

Ambient excitation

Vibration monitoring with ambient excitation is based on the fact that an offshore structure has a series of natural frequencies or resonances that are continually excited by the natural forces of the sea, wind and tide. A change in the stiffness or mass of the structure (or the pile stiffness) will cause measurable change in the natural frequency spectrum. Due to the low damping inherent in jacket platforms, the measured vibration frequency spectrum can be assumed to be solely a function of structural characteristics and independent of the weather conditions. In general, vibration at the lower natural frequencies is associated with the motion of the entire structure and vibration at the higher natural frequencies with the motion of small substructures or individual members.

The amount and distribution of the changes in the natural frequencies due to a member failure or severance depends on the position of the member within the lattice of the structure, on the topology and on the degree of redundancy. The motion of a structure at a natural frequency is known as a mode shape. Typical overall mode shapes are shown in Figure 7.12. Since these overall modes are dependent on the stiffness of the platform, it follows that:

- the more efficient the design (ie the lower its redundancy), the greater the effect on the frequency spectrum; on a highly redundant structure, overall stiffness may not be affected by a single severance
- the position of a member in the structural lattice governs which of the overall modes is most affected by its failure.

Monitoring of a structure is carried out by obtaining vibration frequency spectra from transducers above or below the water line (eight accelerometers, all above water, were used in one monitoring study). Transducer positions are chosen as a result of computer model analysis, which predicts the best signal-to-noise characteristics, and on fatigue analyses and measured/collected fatigue data so that sensor postitioning is directed towards critical zones. The accelerometers are water sealed if placed below water level, and are connected to the recording instruments via cable lengths varying from 30 m to 150 m (or even more).

Because the environmental excitation experienced by offshore structures is of a random nature, the vibration response is also random. Analysis is therefore carried out within the frequency domain using statistical methods. Final analyses of data obtained to date have always been performed onshore, on a time-data computer analysis system.

Typically, frequencies can be obtained to accuracies of 1% and deformed shapes to about 10%. Table 7.4 illustrates results of measurements on a northern North Sea installation.

Vibration monitoring using ambient excitation has been developed to a fully usable monitoring method. One system has been used on at least three North Sea platforms and on one off the coast of Australia. By careful examination and analysis of predicted and measured frequency spectra and deformed shapes at deck level, it should be possible to:

- detect complete severance of a primary member (but not necessarily of a single member in a highly redundant structure)
- detect changes of more than 20% in foundation stiffness
- distinguish between structural damage and changes in deck mass
- locate (approximately) major structural damage.

Forced excitation

Vibration monitoring with forced excitation is carried out by fixing an electro-magnetic or hydraulic vibrator or impactor unit onto the offshore structure. This unit either vibrates the structure at a series of frequencies over a predetermined range or sets up characteristic impulse waves. Any change in the measured vibration signatures is due to changes in the mass and/or stiffness of the structure.

The method can be used locally in part of the structure only or globally throughout it.

The only technique to have been used offshore for local monitoring involves impulse excitation. This technique is concerned with the integrity of individual members or nodes on the structure. It involves no cleaning and requires only one diver for installation. The local excitation is achieved by use of a small impactor, which delivers a single shock wave into the structure. The response can be recorded by the diver using a marinised portable tape recorder or the signal can be transmitted directly to the surface. Although the system has been used for temporary, short-term monitoring, there would seem to be no reason why the equipment could not be modified for permanent installation and continuous monitoring. A reference response curve is recorded and analysed in the frequency domain, and subesquent sets of spectra are compared with it. The initial effect of a crack in a member is loss of stiffness, but if the crack propagates through the wall this leads to member flooding and a change in mass. This in turn leads to a downward shift in the member's natural frequency, which can be detected by comparing the spectrum with the reference. In this way, it is claimed to be possible to detect and locate flooded members, or detect and locate members with a 30% circumferential through-thickness crack at an end weld (provided measurements are taken on the member).

It is also conceptually possible to use a small 'portable' vibrator to induce continued vibration over a range of frequencies in a specific structural area of interest and hence produce a complete vibration signature. Localised analysis of this sort could be used to monitor mode changes (and their frequency shifts) and resonance changes. Resonance changes could be indicative of quite small cracks, material loss through corrosion or marine-growth encrustation. Sweeps to quite high frequencies appear theoretically to provide significantly better sensitivity, making it possible to detect smaller defects. Obviously such methods, if technically viable, could be used either for continuous monitoring (ie permanent emplacement with periodic measurement of responses) or in an inspection mode (with temporary emplacement by diver or ROV during inspection work).

To monitor the whole structure and obtain a frequency sweep of its response would require a large electro-hydraulic vibrator capable of applying vibrations at one or two locations simultaneously, with responses detected by accelerometers at various points on the structure. A single vibrator could be mounted at deck level although a second vibrator at boat landing level would probably activate higher response modes and thus yield more information. It would be necessary to control the force and frequency of the two vibrators and the phase difference between them. An example of equipment layout is shown in Figure 7.13.

The first few resonant frequencies of the response are the important ones. As long as the structure has not sustained damage, the plot of these frequencies should be duplicated in subsequent tests. Damage would show up as changes in the measured frequency signature. The testing and comparison of results by plotting frequency against time could be carried out on a daily (or other periodic) basis. Sudden changes due to damage, deterioration or changes in topside weight could be detected in this way. The technique could also be used to assist in validating the theoretical model used to predict the dynamic behaviour of the structure (by correcting values for deck weight, foundation strength and various damping effects). It could also be used to assess the residual strength of a structure after damage has been sustained.

An obvious problem with forced excitation monitoring is that (ambient) vibrations from environmental forcing may mask responses at low-level forcing frequencies. It should be possible to overcome this problem by modifying the instrumentation, as has been done successfully in the monitoring of a number of land-based structures.

7.5.3 Acoustic emission methods

In its broadest terms, the acoustic emission (AE) method of structural monitoring relies on recording and analysing the elastic waves generated in a crystal structure by the release of internal stored energy. The energy may be released when a flaw or crack is initiated or as it propagates; AE transducers 'listen' for the fault(s) and the data processing equipment analyses where the fault is located. Piezoelectric transducers are used (as with vibration monitoring) to measure the characteristics of the emissions.

One commercially available offshore AE monitoring system can accomodate up to eight sensors. It is claimed by the manufacturer that a minimum of four are required to monitor a K–node to obtain reliable data. They further claim that, under ideal conditions, an active (propagating) crack of 40–50 mm length can be detected and located relative to the weld. The increasing size of an active crack can be determined based on the increasing signal amplitudes from increasing crack surfaces. It has been suggested that this can be used to indicate the approach of failure.

Whether or not an AE monitoring system can detect cracks which are not propagating is not clearly defined. It may be argued that such a crack is stable and therefore of little interest to the structural maintenance engineer. However, from a practical viewpoint, crack propagation is governed by loading conditions and, if propagation does not occur for a certain period, it may simply mean that the type of loading and its severity were not sufficient for crack propagation at that time. The result is that AE should not be looked upon as a crack *detection* method, since it cannot be relied upon to detect unknown, non-propagating cracks.

AE monitoring is widely used for land-based applications and is known to achieve a high level of reliability. Nevertheless, there have been strong reservations about its use offshore and under water. The principal reasons are:

- *Emission characteristics of steels used offshore*
  When AE was first proposed for use on structures fabricated from relatively high-strength (Grade 50D) steels, experiments on specimens with artificial defects tested under increasing loads showed the acoustic emissions to be low level. It was concluded that high-gain signal processing equipment would be necessary, with a consequent lack of analytical sensitivity. In practice, however, emissions from steel under cyclic load (as in offshore use) are much greater than under steady loading, and depend more on the fracture toughness of the steel rather than its strength. Other effects are also significant. For example, the corrosion products forming on the new steel surfaces created by crack propagation under water are brittle by nature, and may give rise to relatively high amplitude signals as the surfaces of the crack come together and separate. Although it may be argued that such signals indicate only the presence of a crack, and do not identify whether or not it is growing, it is possible to distinguish between the two phenomena. In addition, emissions from cracks in weld metal rather than Grade 50D parent steel are known to have much higher amplitudes. On the other hand, however, little is known of the 'noise' characteristics of the high-strength low-alloy steels used in cast nodes.
- *Extraneous noises*
  The signals from structural cracking must be separated from extraneous noises – principally topside and underwater working noises but even the sounds made by marine animals. Recent advances in instrumentation and analysis methods provide effective methods of making this separation. Although frequency filtering has been used in the past, it has not proved to be totally effective. The modern methods comprise:
  - *Spatial filtering,* which is based on the time of arrival of AE signals and original location. This method has the ability to accept signals coming from a specific location in space, while rejecting all others.
  - *Parametric filtering,* which is based on relating the AE signal to the tension portion of the loading cycle, ie the period when crack growth is likely to occur. (This method is easier to apply in the laboratory than in the field and, although not impossible offshore, is very difficult to use successfully.)
  - *Distribution analysis,* which is based on a displayed statistical distribution of signal amplitudes. When a crack is growing towards failure, a higher proportion of high amplitude signals are seen, ie AE signals appear to be proportional to crack surface area.

- *Data handling and personnel requirements*
  AE monitoring generates vast amounts of data, which must be very substantially reduced before results can be interpreted. The reduction can be undertaken at the data analysis point, at the collection point or integrated with the sensors themselves. AE data interpretation should always be carried out by experienced personnel but their efforts are required on an occasional basis only and can be provided by experts working onshore. Data handling methods have been developed to the extent that no skilled personnel may be required offshore at all.

The first applications considered for AE monitoring of offshore structures were for global monitoring, but experience has shown that a system targeted to one localised part of a structure may be more effective. For example, where a defect may already have been detected (by either monitoring or physical inspection), its propagation could be remotely monitored by AE sensors (fixed for temporary or long-term use).

The effective range of an AE transducer depends on the type of structure (AE monitoring can be used on concrete as well as steel offshore structures), the operating frequency and the type of steel. For example, frequencies between 100 kHz and 1 MHz have been suggested for Grade 50D steel, with a typical range for upper frequencies being about 5–6 m (the lower the frequency the greater the range).

7.5.4 Cathodic protection condition

There are good reasons for continuosly acquiring data on a structure's cathodic protection system. Divers can check the condition of the system during annual inspections (see Section 7.2.2) but its effectiveness may deteriorate during the winter months when diving is not possible and agitation of the sea during storms may cause depolarisation of the steel, resulting in lower CP potentials during winter months. CP data continuously acquired during the first 12 months or so after installation also provides data which can be used to confirm the adequacy of the CP design.

A CP condition monitoring system requires strategically placed underwater sensing equipment (normally half cells), reliable data transmission facilities to the surface and analysis equipment. A number of North Sea operators have installed such systems during structure fabrication, but in almost all cases the data transmission systems have been damaged – due to environmental factors or, more likely, accidental operational interference.

The need for CP condition monitoring is appreciated by the offshore industry, but the problems associated with continuous data acquisition have in the past proved insurmountable. However, new techniques such as taut-wire and acoustic through-water transmission may now allow operators to gain the benefits of CP monitoring – not only on new installations but, more importantly, by retrofitting on older structures as well.

7.5.5 Steelwork internal pressures

Many of the tubular structural members of an offshore jacket structure can be designed to be sealed units normally filled with air. Should a through-thickness crack develop in any of these members there will be a change in the internal air pressure within the member – either a decrease or an increase depending on the original internal air pressure and the depth of sea water at which the crack has developed. (The only conditions at which there will be no change is when a crack occurs at a depth where the seawater pressure is exactly equal to the original internal pressure.)

This principle has provided the basis for a condition monitoring method. In practice, several of the members can be made to communicate internally so that a larger 'zone' of members can be monitored, and the whole zone can be pre-pressurised to any specified level. When a crack causes the internal pressure to change, instrumentation can provide immediate warning of the occurence (see Figure 7.14) and, to some extent, the location of the defect.

A monitoring system of this sort is currently installed on platforms off the coasts of Indonesia and Abu Dhabi. The zones are pressurised with air to approximately 2 bar g. Conventional cabling is used for data transmission but there seems to be no reason in principle why acoustic through-water data transmission could not be used with data at a characteristic frequency collected from each individual zone at a central underwater point for onward transmission to the surface.

Installation of this type of monitoring system should provide no difficulties at the fabrication yard but retrofitting to existing platforms appears far less practical.

7.5.6 Fibre-optic crack monitoring

A method of local monitoring to detect cracking at predetermined points on the surface of an underwater structure is under development, using optical fibres. Fibres rigidly bonded to the surface of the structure will transmit light while they remain intact but fail to do so when they break after surface strains are reached beyond the strain limit of the fibre.

The principle of operation is illustrated in Figure 7.15. A complete package would consist of:

- a set of fibres (say 8 core with diameter range 50–200 μm)
- a transmitter (a suitable light source operating at a wavelength to give minimum attenuation, eg an infra-red (800 μm) light emitting diode)
- a receiver (to receive the light transmission – photo diode detector)
- connectors (for optical jointings).

Even if the surface crack is small, producing only a slight separation of the broken fibre ends, there will still be sufficient loss of transmitted light to enable the discontinuity to be detected. Optical fibres can be specially treated to fracture at specified levels of strain, eg 0.5% or less.

The sensitivity of the technique depends on the degree to which the ductility of the fibres and the adhesive can be matched to that of the substratum, and on the strain transfer capability of the bonding agent used to fix the optical fibres to the steel surface. The geometrical arrangement of the optical fibres is also critical; unless the crack propagation crosses the path of one of the fibres, it may go undetected.

The system can detect crack widths as small as 20 μm. It is also possible (if long runs of fibres are used) to locate the crack by using time-domain reflectrometry.

7.5.7 Performance-based monitoring

Methods have been developed to monitor the performance of structures in service to compare the actual structural performance with predictions made at the design stage. The parameters measured for this purpose have been strains, tilt, subsidence, etc. Although these methods are not primarily intended to identify unexpected deterioration or failures within the structure, further development of them may make them suitable for this purpose.

Strain gauges

Strain gauges are now available with the transducers encapsulated in stainless steel to make them suitable for underwater use. The data obtained from strain gauging offshore structures have been used to compare measured strains with basic design-loading assumptions. However, the reliability of underwater strain gauges is still questionable, and the prospect of a 30-year life is not yet a practical one. Failure rates of up to 40% in a 4-year period have been reported. There would also be problems with the extensive and complex wiring that would be necessary to monitor large areas of structures. These factors may explain why strain gauging has, to date, only been used for monitoring specific conditions over relatively short periods.

Inclinometers

Monitoring for any tilt in a platform's attitude could provide a warning of differential movement of foundations and is highly likely to indicate major deterioration of the structure before collapse. There is no shortage of suitable techniques for measuring this parameter, eg:

- a water levelling device is claimed to achieve accuracies in the range of tenths of a millimetre in levels 100 m apart, with greater accuracies over shorter distances
- a spirit level is available and capable of measuring changes in attitude with an accuracy of ±15 seconds of arc
- an 'electro-level', using an accelerometer to measure angular changes, has been developed and is sensitive to changes as small as 1 part in 2×10^5 (10 mm in 2 km). It is used for pile monitoring on at least one major North Sea oil field.

There are however some limitations to these methods and although they could be considered as essential, the equipment available does not yet satisfy the aims of a true condition monitoring system.

Air gap and differential settlement measurements

Although not strictly inspection, there are occasions when measurement may be required to monitor settlement of fixed installations to ensure that the 'air gap' is maintained. (The air gap is the clearance between parts of the superstructure not designed to resist wave impact and the highest foreseeable design wave crest superimposed on the highest foreseeable still water level.) In order to demonstrate that the design requirement is maintained, it is necessary to monitor the air gap. This may be performed in a variety of ways from suitable datums, either topsides or subsea, and may be discrete or continuous with reference to the water plane at a given tide and time. Some contractors offer a service using satellites but the accuracy, based upon the percentage error and the distance of the satellite from the installation, is questionable. This information then requires to be referenced to a tilt survey carried out with a 'dumpy' level or inclinometer. At least one North Sea operator uses an infra-red wave height sensor output, programmed to remove residual influences to produce a trend from a mass of data. Although the equipment manufacturer quotes 1% accuracy (at 25 m) from experience, the operator considers the accuracy to be better than this, ie in the region of 0.5% and considered sufficient for his needs.

7.5.8 Crack propagation monitoring

The principles and techniques of monitoring can be used to measure the progress of *known* defects as well as monitor for the appearance of *unknown* defects. To date, a defect once detected has received continuing and careful attention during subsequent inspection programmes. This has proved costly in terms of dive time and suffers the disadvantage that the defect is not checked at all between diver and/or ROV inspections. As monitoring methods continue to develop, it becomes clear that many of them are suitable for temporary installation at sites of defects discovered during inspections so that defect propagation can be continuously monitored. The monitoring system would be 'tuned' to give fine sensitivity, would operate only to give a very local coverage and would be designed for temporary installation, not permanent.

Of the monitoring methods already described, the following would be suitable for this purpose:

- vibration monitoring (see Section 7.5.2)
- acoustic emission monitoring (see Section 7.5.3)
- fibre-optic crack monitoring (see Section 7.5.6).

Other underwater NDT methods also have potential for this continuous monitoring role:

- Alternating current potential drop method (see Section 7.2.9)
  A number of ACPD electrodes fixed in position at the site of an existing crack and along its anticipated propagation path would be able to monitor increases in crack depth. A crack may often veer off in unexpected directions but it should be posible to arange a matrix of electrodes to cover all likely crack paths.
- Ultrasonic methods (see Section 7.2.5)
  Similarly, crack growth could be monitored by ultrasonic probes (pulse-echo or through transmission) fixed to the cracked member.

7.5.9 Flooded member monitoring

The ability continuously to monitor a number of strategic members of an offshore structure for flooding could yield information on the integrity of the structure, and indicate the increase in loading on the structure (due to the entrapped water). Some of the methods discussed earlier – monitoring methods and inspection methods – have potential to be used in this way, eg:

- vibration monitoring (see Section 7.5.2)
- ultrasonic transmission/blocking (see Section 7.2.6).

Table 7.4: *Vibration monitoring results due to damage[1] on a northern North Sea platform*

Mode[2]	Frequency change (%)		Change in deformed shape ratio (%)	
	Predicted	Measured	Predicted	Measured
1. North-south	–3.2	–3.8	16	17
1. East-west	0	0.6		
1. Torsional	–1.7	–1.9		
2. North-south	–0.2	–0.4	–19	–15
2. East-west	0	–0.1		

1 The damage is member severance on the west face

2 See Figure 7.12

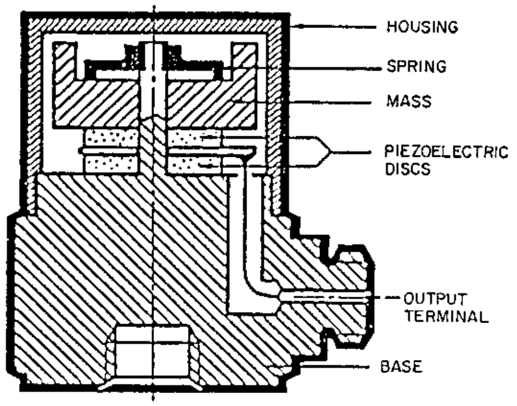


Figure 7.11: *Cross-section of a typical piezoelectric accelerometer (Courtesy of B&K (UK) Ltd)*

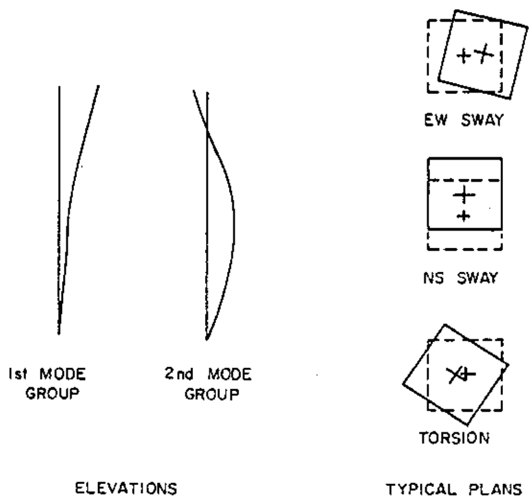


Figure 7.12: *Typical overall mode shapes from vibration monitoring*

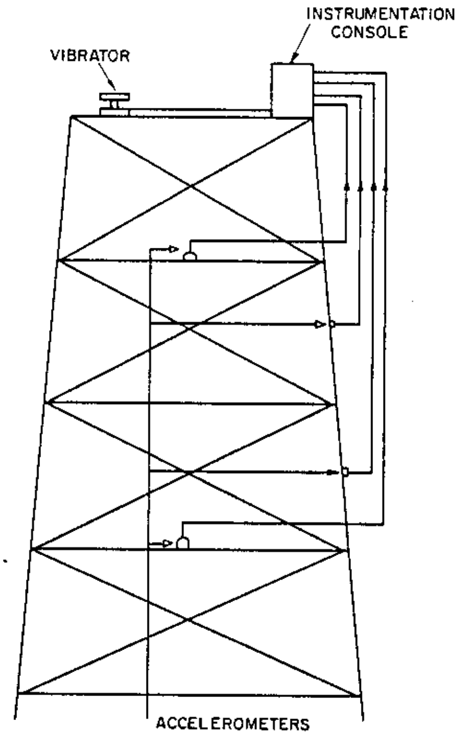


Figure 7.13: *Layout of the components of a forced excitation vibration monitoring system covering a complete platform*

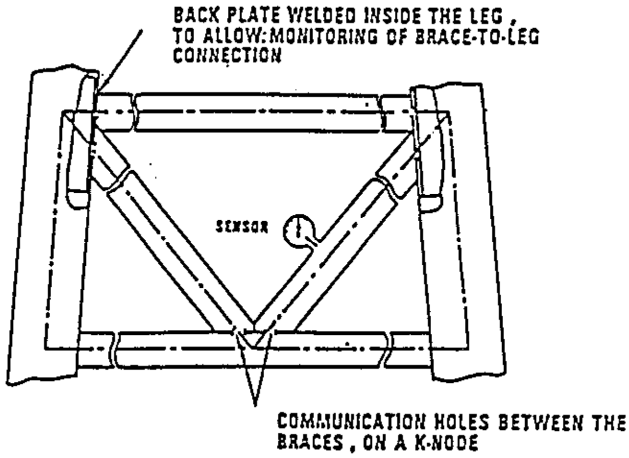


Figure 7.14: *Principle of operation of monitoring steelwork internal pressures*

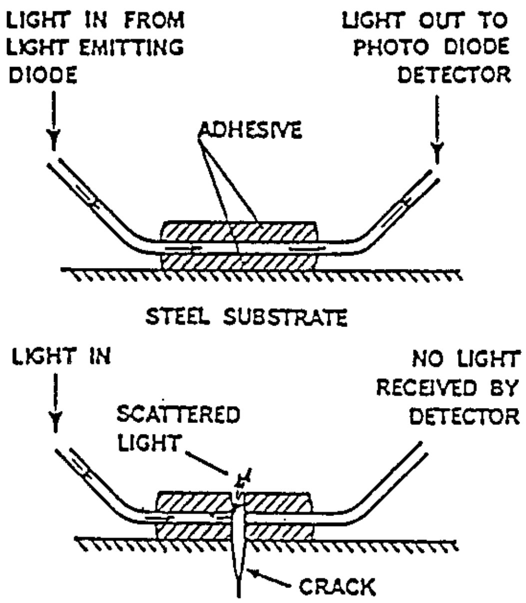


Figure 7.15: *Principle of operation of fibre-optic crack monitoring*

7.6 SPECIAL INSPECTION APPLICATIONS

7.6.1 Inspection in deep water

The method of intervention to be used to make access to an underwater inspection site is to some extent dictated by the water depth. The depth limitations of the four intervention methods discussed in Section 7.4 are listed in Table 7.5 together with their associated inspection limitations. Clearly, 'diverless' inspection methods must be used at depths greater than 300 m and development of remote, automatic, robotic and/or 'teach and learn' inspection systems can be expected.

The increased water pressure at greater depths is not expected to affect the physical basis of the underwater NDT methods currently used in relatively shallower water. Nor is it expected to affect the equipment itself provided adequate engineering precautions are taken.

7.6.2 Export risers and conductors

Although the export risers, conductor casings, bracings and framing on a platform are not part of the primary structure, their integrity is essential to the safe, efficient and economic functioning of the whole installation. Full and effective inspection of these components is therefore essential.

Corrosion and anodes

Risers and conductors are usually cathodically protected and the inspection methods used to check CP systems on the primary structure should also be applied to these 'secondary' components:

- the polarised electrical potential of the structure in water should be measured with respect to a specified reference electrode to determine whether it conforms to the original design specification
- the flux or current density should also be measured
- the structure should be in metallic contact with the anode.

A check should also be made that corrosion damage has not occurred and, if it has, it should be quantified by determination of wall thicknesses. Although most types of corrosion are quite obvious, general corrosion (especially general internal corrosion) may not be, and wall thickness measurements are normally required as part of every riser and conductor inspection.

Visual methods (see Section 7.2.1) are an essential part of every inspection for riser and conductor corrosion, supplemented by CP measurements (Section 7.2.2), ultrasonic wall thickness measurements and pit depth measurements (Section 7.2.3).

Protective coatings

Risers and conductors may be coated, primarily to give protection against corrosion but also to give protection against physical impact damage in some situations. The coatings may be paint, epoxy, bitumen, or in some cases reinforced concrete.

All coatings should be inspected regularly to ensure that they are intact and undamaged from impact, corrosion or deterioration due to ageing. Visual methods are normally adequate for this task (see Section 7.2.1).

Fixing clamps

Risers and conductors are attached to the primary structure by bolted clamps. Although the clamps are designed to permit some movement between riser and structure as the main structure flexes, they can become loosened. Regular checking is necessary for fit, tightness, and possible damage.

Where excess movement has occurred, fretting between riser and clamps may remove either the corrosion-protection coating or an acceptable covering of corrosion product. In either case, the corrosion process can accelerate and become potentially very dangerous. Therefore, besides checking the clamps and their fit it is also important to detect fretting/ corrosion damage at or near the clamps.

Visual methods are normally adequate for this task (see Section 7.2.1), supported by manual checking of the tightness of bolts or nuts.

7.6.3 Secondary components and attachments

By their nature, secondary components such as boat landings, fenders, bumpers and hand rails are not essential to the well-being of a primary structure, but are invaluable with regard to personal safety and operational facility. The main difference between inspecting these components and primary structural components lies in the fact that they are rarely subject to cyclic fatigue loading (and, when they are, fatigue is less significant than for primary components) but are particularly prone to impact damage, especially from boat collisions.

The prime inspection tasks therefore are to detect visible impact damage such as dents and buckles and any cracking in the vicinity of the dents and buckles and possibly in weldments. Visual inspection is primarily used in this work (see Section 7.2.1), supplemented wherever appropriate by MPI examination (Section 7.2.4) for the presence of cracking. In general terms, MPI should be performed wherever impact evidence is found – in the vicinity of the evidence and on all welds associated with the damaged area or component.

7.6.4 Seabed pipelines

Seabed pipelines are the essential 'arteries' of offshore oil and gas operations. Failure of a flowline (ranging from a minor leak to complete rupture) would lead to loss of product and revenue but, of greater concern, would also lead to environmental pollution damage.

Every factor that may influence flowline integrity must be inspected regularly, carefully and effectively:

- *Corrosion protection*
  Cathodic protection anodes are usually fixed at intervals along the line. As with any CP system, it is essential to check that the system is working effectively and that corrosion damage has not taken place. Visual methods must be used (see Section 7.2.1), supplemented by CP potential and current density measurements (Section 7.2.2) and physical checking of the anodes.
  Flowlines carrying product with a high wax content may be insulated to retain natural heat and prevent wax solidification and pipe blockage. Because there would be considerable difficulty in preventing sea water penetrating the insulating layers at the sites of CP anodes and reaching the pipe steel, it is easier to exercise a very high level of care in applying the insulating coating to ensure complete separation of the steel from the sea water electrolye than fitting anodes. As a result, such flowlines must receive special care in inspection, which by its nature is largely achieved by close and carefully applied visual techniques (see Section 7.2.1).
- *Concrete weight coating*
  Where seabed pipelines are unburied, the concrete weight coating is prone to accidental interference and damage by anchors, fishing nets, etc. Serious damage can be caused to the precast coating and the field joints. Visual inspection is essential (see Section 7.2.1).
- *Seabed movement*
  Movement of the sea bed can seriously affect the integrity of any seabed flowline (whether buried or not). The line can physically move position laterally, and loss of cover over and support under the line can cause stresses and loads not allowed for in the design. Unsupported 'free spans' introduce loads which increase in severity with the length of the span. The detection, location and quantification of free spans and lost cover is one of the most important aspects of flowline inspection. Careful and accurate physical measurements must be made of span heights and widths.
- *Flexible flowlines*
  Flexible flowlines (usually 75–150 mm in diameter but up to a maximum of 400 mm) are used as satellite flowlines and water and gas injection lines. They are manufactured from high quality materials including a plastic covering to prevent sea water reaching the structural layers. They are supplied in virtually endless lengths. Unless physically damaged they require no inspection other than regular visual observation of their integrity and stability (see Section 7.2.1).
- *Bundled flowlines*
  Bundled pipelines (first used in 1979/80) consist of a number of small lines held by plastic spacers within a large carrier steel pipe. The bundle is manufactured onshore (in lengths up to several kilometres) and towed to the offshore installation site. Inspection is generally the same as for conventional seabed lines, and normally

achieved by visual ROV observation (see Section 7.2.1) and corrosion monitoring (Section 7.2.2).

7.6.5 Seabed production equipment

Wellheads and manifolds

The inspection requirements of seabed wellheads and manifolds are:

- *corrosion inspection* – as for other underwater CP-protected steelwork (see Sections 7.2.2 and 7.2.3)
- *internal erosion of pipework* – may occur from sediments in the crude oil. Methods for detecting this include ultrasonics (see Section 7.2.3 and 7.2.5), thermography and radiographic tomography (see Section 7.2.11)
- *surface-breaking fatigue cracks* – can be identified by MPI (see Section 7.2.4) although special techniques may be necessary, eg eddy current testing (Section 7.2.8), the AC potential drop method (Section 7.2.9), etc.

Underwater radiography of welds on seabed wellheads and manifolds cannot be justified by either good radiographic practice or Standards requirements. It should only be considered in extraordinary circumstances. The only possible exception would be using real-time radiographic techniques (see Section 7.2.7) where the energy beam and workpiece can be continually realigned in relation to each other. Even in this case, highly specialised procedure specifications (see Section 7.1.1) would be essential.

Templates

Seabed templates act as physical restraints only. They do not carry fluids at high pressures and temperatures and so the potential for internal corrosion and erosion does not exist. With this exception, the inspection of templates is similar to the inspection of wellheads and manifolds (see above). However, although the crack detection methods may be identical, the specific techniques used need to be different, because templates have quite different geometries to wellheads and manifolds and they have many more fillet welds which by their nature are best inspected by different techniques.

7.6.6 Inspection pigging

Pigs are passed through pipelines for a variety of operational and maintenance reasons including cleaning, removing liquids, swabbing and drying, scraping hard scale, gauging, separating products and .... inspection. Inspection pigs are usually designed to detect internal corrosion and assess levels of cathodic protection. Other sensors may be used, but the present-day limits are considerable.

7.6.7 Non-jacket platforms

Flotation tanks

Cracks have been known to propagate in the fillet welds near the toes of gusset strengtheners in the flotation tanks of compliant platforms and towers. To overcome access problems in these areas, flux path (ie magnet-based) techniques have commonly been used to provide the magnetisation for MPI (see Section 7.2.4). However, these techniques are not appropriate and results have been inconsistent. A technique based on jigged insulated coil and conductor is much more appropriate and should, at one and the same time, solve the access and consistency shortcomings.

Guy wires and chains

On compliant floating installations, deterioration of the guy wires and chains and the components connecting them to other parts of the structure are of particular importance. The main problems are:

- *Corrosion, chafing and fretting*
  General corrosion is potentially important for every chain link, but chain geometry can make it particularly difficult to inspect for this in any definite way. The problem can be made significantly worse by continual fretting between the links, possibly resulting in accelerated fretting corrosion. Relevant inspection can be by through-material measurements using ultrasonic techniques (see Section 7.2.3) and/or physical measurements using calipers or similar equipment – but only for accessible parts of each link.

Concentration cell corrosion, stress corrosion, corrosion fatigue and biological corrosion may also occur – for chain links and for wire elements – but it is not currently possible to detect and quantify these types of corrosion in any practical way.

- *Cracking of chain links*
  Similarly, detection of cracking in chain links is not presently believed to be a practical possibility. However, eddy current inspection techniques (Section 7.2.8) and the resonance vibration monitoring technique (Section 7.5.2) seem potentially suitable for this task, possibly semi-automated by developing a specific tool to be applied to each link in turn. An eddy-current tool could be based on a jig with an appropriate matrix of EC coils; a standard response from a known 'good' link would be compared with the responses from in-service links. Using resonance vibration principles, the link above (and to a reduced extent the link below) the one under test would be restrained, and an impact blow of a standard force would be applied to the test link. Monitoring of the resultant resonances and comparing them with those from a standard 'good' link may give an indication of the link's condition.
- *Broken wire strands*
  The eddy current and resonance vibration techniques outlined above may also be capable of indicating that some strands of a cable have parted. A shock-wave method also appears to be conceptually possible. This would involve applying a shock wave into the end of the cable. Should any strands be broken, the position of the break could be determined from the return time of the shock wave.

Articulated joints

Inspection for corrosion of the universal joint at the base of an articulated tower could follow along similar lines to those described for corrosion of chain links above. Methods of inspection for wear at the joint's surfaces are dependent on the specific geometry and service conditions of the joint, and it is difficult to offer general guidance on this subject.

Tendons of tension leg platforms

The tendons (or 'legs') of a tension leg platform may possibly be up to 900 mm in diameter and 100 mm in wall thickness. On the Conoco Hutton platform the dimensions are 270 mm and 92 mm respectively. The parts of the tendons requiring most inspection effort are the connections – threaded connections as at Hutton, or possibly welded connections.

The type of defect most likely in threaded connections is suggested to be cracking at the base of the threads. This is an area that is difficult to inspect at the best of times, ie when the two components are unthreaded and in air. Inspection in these circumstances is normally performed by specialised MPI techniques (see Section 7.2.4), although the eddy current method (Section 7.2.8) could be more beneficial if a technique could be engineered for the task. Where the connections are permanently threaded together as in a TLP, neither of these methods are seen as being possible in any circumstances. Other inspection methods that could then be considered are:

- *Ultrasonic method* (see Section 7.2.5)
  Ultrasonic methods have the advantage of being able to detect volumetric as well as surface defects from the inside of a tendon, but careful design is needed to optimise inspection coverage. In general, the achievable resolution for defect detection and sizing is likely to vary for different positions along a threaded coupling. After consideration of alternative methods an ultrasonic inspection system was developed for deployment down the internal bore of the Hutton platform tendons.
- *Radiographic method* (Section 7.2.7)
  It may be possible to use a radiographic technique with the energy source inside the tendon and the receiver outside (although the need for external access under water would make practical implementation difficult and costly). A variable intensity x-ray source and real-time receiver would be preferable although γ-rays and film are also seen as being possible. The radiographic possibilities are largely dependent on the difference from the normal angle of both the thread rises and on the anticipated orientation of any cracks.
- *Potential drop method* (Section 7.2.9)
  It is also conceptually possible that a potential drop technique could be developed for the task. It is unlikely that alternating current techniques would be suitable, but direct current techniques deserve to be studied in relation to the geometries of particular connections.

- *Eddy current method* (Section 4.8)
  Consideration of the theory of eddy current testing suggests that it should be possible to use the method to detect the anticipated type of thread cracks from the unthreaded surfaces. To be successful, any technique would require internal and external coils searching for the defects in each thread component. Once again, the requirement for access to the outside of the tether, and the need for surface cleaning, would present practical difficulties.

In principle, monitoring methods may be able to complement – or in some situations replace – inspection for this task. The extent to which monitoring could be used would depend upon the required defect parameters for detection and sizing (which would be determined by fracture mechanics evaluations during tether design), together with the performance of the monitoring method. Large-scale monitoring methods are unlikely to provide accurate sizing capabilities without the placement of very large numbers of sensors.

Installation of any monitoring sensors in the tendon bore would be comparatively easy, condition data would be continuously available in real time and there would be no need for specialist NDT technicians to be onboard the installation when readings were being taken. Occasional monitoring (see Section 7.1.4) could be carried out using a cable with one sensor array lowered through the tendon bore when data were required, or a cable with a sensor array for each tendon connection could be left in the tendon permanently to provide the benefits of continuous monitoring. The following condition monitoring methods appear to be conceptually possible:

- *Acoustic emission* (see Section 7.5.3)
  For this to work it would be necessary to separate crack propagation noises from the thread's abrasion noises and the noises of crack opening and closing. Brief consideration of present knowledge and current developments suggests that this may be possible in the future.
- *Ambient vibration monitoring* (Section 7.5.2)
  It is suggested that this approach may have potential for a preliminary monitoring study at coarse sensitivity.
- *Forced 'impact' vibration monitoring* (Section 7.5.2)
  Just as with castings, railway wheels, etc, a cracked thread may respond quite differently from a sound one.
- *Resonance vibration monitoring* (Section 7.5.2)
  Frequency sweeps to about 25 kHz would be used. As with the impact vibration technique, it may be possible to differentiate the resonances of cracked threads from those of undamaged threads.
- *Potential drop method* (Section 7.2.9)
  DCPD techniques are mentioned above as an inspection approach but, conceptually, they could also be applied in a monitoring mode – if study of the theory suggests adequate validity for this particular workpiece configuration.

The inspection task would be easier if the tendon legs had welded rather than threaded connections. There is very considerable offshore experience of inspecting welded joints using ultrasonic techniques and a number of probe configurations would be appropriate for this task. The other inspection and monitoring techniques outlined above as being suitable for threaded joints may also be appropriate for welded joints too. In general, because the configuration of a welded joint is simpler than the geometry of a threaded connection, the NDT techniques can also be simpler.

Table 7.5: *Depth limitations of intervention methods*

Intervention	Approximate depth limit (m)	Inspection capabilities	Inspection deficiencies
Diving	300	All present requirements except crack sizing	Crack sizing
Atmospheric diving suit	700	Visual inspection Cathodic protection current density Ultrasonic thickness measurement	Crack detection Crack sizing
Remotely operated vehicle	1000(1)	Visual inspection Cathodic protection current density Ultrasonic thickness measurement Cleaning(2) Magnetic particle inspection(2)	Crack detection Crack sizing
Submersible(3)	1000(1)	Visual inspection Cathodic protection potentials	All other tasks

1 More in some cases
2 Currently under development
3 Divers from a lock-out submersible have all the 'diving' capabilities

8 Assessment of damage

8.1 THE ROLE OF DAMAGE ASSESSMENT

There are two contexts in which it may be necessary to perform an assessment of structural damage to an offshore installation:

- *Damage assessment before performing an inspection*
  In this case the assessment is performed for postulated damage, with the aim of determining the type of damage which must be detected and the required frequency of inspection. This type of study is particularly suited to fatigue cracks, for example. The rational approach to inspection planning described in Chapter 5 outlines typical assessment studies of this sort in Section 5.2.5.
- *Assessment of damage after performing an inspection*
  The objective of this type of assessment is to determine the significance of actual damage which has been detected in an underwater inspection. The findings would be used to make a 'repair/no repair' decision or to determine a programme of future inspections for the damaged area.

In this section, assessment methods are given for the most commonly occurring types of damage, namely dents and fatigue cracks, and a brief review is given of methods of redundancy analysis. By definition, damage assessment is not covered by design codes, and so non-codified methods are presented.

It is not possible within the scope of this document to perform a comprehensive review of assessment methods, and so the methods presented have been carefully selected as being the most suitable for use in practical situations.

8.2 DENTED AND BENT MEMBERS

8.2.1 Types of damage

Damage to members of offshore steel structures is sometimes caused as a result of collisions with supply boats or by falling objects. The members in a jacket structure which are most likely to be affected by boat impact are vertical and diagonal members located in the splash zone. These members are loaded in compression due to the topside dead weight, and therefore fail through lateral buckling.

From experimental tests and in-service experience the damage has been found to have the following forms:

- local denting of the brace wall without any overall bending of the member – this situation occurs mainly in short members with large diameter/wall thickness (D/t) ratios or at the ends of brace members
- overall bending of the brace without any local denting – this situation occurs mainly in long members with small D/t ratios, due to impacts near mid-span
- a combination of local denting and overall bending of the brace – this situation is the one most commonly encountered in practice
- fracture of the member due to its ultimate axial tensile capacity being exceeded as a consequence of gross deformation and subsequent membrane tension yielding
- in addition to damage to the impacted member, the adjacent joints may also be damaged if the ultimate capacity of the member exceeds the ultimate capacity of the tubular joint.
- adjacent members may be damaged if they are not sufficiently strong to absorb the end forces from the impacted member.

Damage to a tubular member can be classified as minor if its ultimate load capacity has not been reduced (as a consequence of the damage) to a value less than the maximum applied load. Similarly, severe damage can be considered to have occurred when the reduced ultimate load capacity of the damaged member has been exceeded by the applied load. In this situation the damaged member can only sustain its post-collapse load, and the balance of the applied load must be re-distributed to adjacent members.

8.2.2 Review of published literature

A large amount of theoretical and experimental research has been undertaken since 1979 into two related areas of damaged members:

1. investigation into the mechanisms for a tubular member to absorb energy from a lateral collision Wed, Jun 7, 1989with a supply boat or from a dropped object
2. investigation into the residual strength and stiffness of a tubular member which has suffered from a lateral collision.

The findings from Item 1 above are of primary interest during the design of a jacket as it is possible to quantify the damage incurred for a given impact energy. This information can subsequently be used to ensure that the global structural integrity is not compromised by local damage.

Some of the more recent developments in this area are due to Richards and Andronica[8.1], Ellinas and Walker[8.2], and Pettersen and Johnson[8.3]. The method proposed by Richards allows the impact energy to be absorbed, in the correct proportions, by the following mechanisms in a tubular member with various end conditions:

- energy absorbed by elastic deformation
- energy absorbed by local denting
- energy absorbed by formation of plastic hinges
- energy absorbed by membrane tension yielding

Figures 8.1 and 8.2 show the results produced by the mathematical model of Reference 8.1 for two simply supported tubular members. These models are based on data from members of offshore structures which have been damaged. The relevant details of the members are given in Table 8.1. Several points of general interest can be seen from inspection of these two figures:

- Impact energy is absorbed firstly by elastic bending and dent formation until a mechanism develops due to the onset of plastic hinges.
- The dent depth and total resisting force remain virtually constant after the formation of a mechanism. The magnitude of the resisting force is maintained at large lateral deflections due to a significant contribution from the membrane tension yielding effect.

The majority of the recent research in Item 2 in the list at the beginning of this section has been conducted by Smith[8.4, 5, 6, 7, 8], Taby and Moan[8.9], and Ellinas[8.10]. This work has been directed towards computing the residual strength and stiffness of damaged tubular braces with simply supported end conditions and, to a lesser extent, with general rotational stiffness at the member ends.

A detailed description of the findings of the above work and methods of using this information to aid defect assessment is presented here in Sections 8.2.4 to 8.2.6.

8.2.3 Buckling behaviour

The buckling behaviour of tubular members can take either of the following forms (or a proportion of both):

- column buckling
- local buckling.

It is important to establish if local buckling is liable to have a controlling influence in the buckling behaviour of a tubular brace since the post-collapse behaviour of damaged (and undamaged) tubular members is catastrophic in such circumstances.

Column buckling

Column buckling is an overall effect which takes the following forms:

- long, slender tubular columns ($\lambda \geq 1.5$) fail by elastic buckling at the Euler stress
- as λ reduces from 1.5 to 0.0 the column failure becomes increasingly controlled by inelastic buckling and by the compressive strength of the material.

In the above, λ is the reduced slenderness ratio, defined by:

$$\lambda = (F_y/E)^{1/2}(L/r)K/\pi \tag{1}$$

where F_y = material yield stress
(L/r) = the actual slenderness ratio of the column
K = effective length factor.

These two regimes of column buckling are clearly illustrated in Figure 8.3.

Local buckling

Local buckling occurs when a local 'bulge' or 'lobe' forms on the surface of a tubular. This from of buckling becomes increasingly dominant as the D/t ratio exceeds 60. The classical failure stress, F_u, for local buckling of perfect thin cylinders in a periodic mode with 'diamond' shaped lobes is:

$$F_u = 1.21Et/D \tag{2}$$

However, for the typical bracing members used in offshore structures, which are fabricated from a series of rolled plates ('cans'), the local buckling mode takes the form of an axi-symmetric bulge rather than the classical diamond lobes. This bulge can occur at the member ends or, as shown in Figure 8.4, at circumferential butt welds between adjacent cans. In this situation it has been found that the local buckling stress has the form:

$$F_u = F_y - 0.0012\,F_y D/t \tag{3}$$

A more conservative estimate of the local buckling strength of typical offshore tubular members is given in Reference 8.10 as:

$$F_u/F_y = 1 - 0.0024(D/t) + 0.000003(D/t)^2 \tag{4}$$

The effect of local buckling failure on the ultimate axial capacity of an undamaged tubular member has been illustrated in Reference 8.10 and reproduced in Figure 8.5. Tubular members which are susceptible to local buckling and have in addition suffered bending or denting damage will exhibit a further loss of strength from that shown in Figure 8.5. This aspect is discussed further under 'Dent damage' in the next section.

8.2.4 Residual strength and stiffness

The analytical method which is developed in this section to assess the residual strength of bent and dented members is based on incremental elasto-plastic large displacement beam-column analysis. The pertinent features of this type of analysis are summarised as follows:

- The tubular brace is idealised as a series (typically 20) of straight beam elements. The lengths of individual elements usually vary to allow small element lengths to be used in areas where plasticity is expected.
- The tubular cross-section is divided into element 'fibres' as shown in Figure 8.6, thus allowing the progressive development of plasticity over the member cross-section.
- Loads are applied incremently with a linear solution being obtained at each increment from the following equation (from Reference 8.4):

$$(K_t + K_g)u = P \tag{5}$$

  where u = nodal deflections
  P = applied load
  K_t = incremental stiffness matrix based on the tangent stiffness matrix
  K_g = geometric stiffness matrix.
- Damage to a member resulting in permanent bending is modelled by specifying initial lateral deflections at the element nodes.
- Following the methods proposed by Smith[8.7], damage to a member resulting in the formation of a dent is modelled by reducing the values of Young's modulus and the yield stress for the 'fibres' in the dent zone (see Figure 8.7). the resulting bi-linear stress/strain curve is shown in the figure where, for a dent of depth d, k is given by:

$$k = 0.59 - 0.0096D/t + 0.0003E/F_y - 0.57d/D \tag{6}$$

  The expression for k has been established by correlating the analysis procedure described above with experimental tests on damaged tubular members and using a least-squares method to fit the equation to the data points. Upper and lower bounds on the collapse strength of a damaged tubular can be obtained by setting $k = 1$ and 0 respectively. Typical experimental values for k lie in the range 0.2 to 0.4.

- Dent damage is modelled by Taby and Moan[8.9] by an analytical method as shown in Figures 8.8 and 8.9. In this model the undamaged section of the tubular is modelled by an offset beam and the load carried by the dented region is applied as an offset point force, Q. For a compression member, Q is given by the following semi-empirical equation:

  $$Q = 80tF_y \cos^{-1}(1 - 2d/D)C \qquad (7)$$

  where $C = (4n^2 + t^2)^{1/2} - 2n$

  and n is defined in Figure 8.9.

The development of the computer models mentioned above has enabled a wide range of damaged tubulars to be studied with the results being verified against experimental results where possible. Using the results of these studies, the effects of various parameters on the residual stiffness and strength can now be discussed.

Bending damage

The effect of varying the slenderness of the damaged member (expressed in terms of λ, the reduced slenderness ratio) is shown in Figures 8.10 and 8.11 for simply supported and clamped tubulars[8.4]. In these examples, D/t and E/F_y are held constant at 35 and 638 respectively. It can be seen from these figures that by choosing $K = 0.6$ for the clamped tubes the residual strength characteristics are almost identical for an equivalent value of λ. The damage effects are most marked in the post-collapse range of tubulars with a λ value lying in the imperfection-sensitive range $0.7 \leq \lambda \leq 1.1$.

The shape of the initial bending damage has been found to have a negligible effect on the residual strength compared to the maximum magnitude of the initial lateral deformation. The forms of bending damage that have been considered consist of sinusoidal, parabolic and bilinear (ie 'dog leg').

The effect of varying the initial bending damage can be seen from Figures 8.10 and 8.11 to dominate post-collapse behaviour for low-λ tubulars and pre-collapse behaviour for high-λ tubulars.

The effect of residual weld stress from a seam weld on the strength of compressed undamaged tubulars is shown in Figure 8.12 for varying values of η. The form of the residual stress field for this situation, together with the definition of η, are shown in Figure 8.13(a). Typical values of η for offshore tubulars are about 4, which normally affects the member strength by less than 10%.

The effect of a residual stress distribution of the form shown in Figure 8.13(b) (which occurs in bracing members with bending damage) has been found to have a negligible effect on the residual strength of a damaged tubular. Figure 8.14 shows the effects of the residual stress distribution on residual strength for a tubular member with three levels of bending damage.

Dent damage

Experimental results show that residual strength of a dented tubular is a function of the depth of the dent and does not depend on the shape of the dent. This conclusion was reached after testing tubulars with 'knife edge', 'round' and 'square' dents.

The effect of the location of the dent along the length of the tubular has a negligible effect on the residual strength, as shown in Figure 8.15. The figure also shows the negligible effect that the length of the dent (measured along the tube axis) has on the residual strength for a given dent depth.

Typical load-deflection (ie load-shortening) characteristics for a tubular susceptible to a local buckling failure are shown in Figure 8.16. These characteristics were obtained experimentally[8.5] for tubes with $D/t = 87$, $L/r = 48$, $E/F_y = 470$ and three levels of dent damage. The sudden and drastic loss of strength following ultimate load is characteristic of a local buckling failure and shows that such tubes should not be used for bracing members which may suffer collision damage.

After occurrence of dent damage a subsequent increase in axial compression load will not increase the dent depth until the residual ultimate strength is achieved. However, the post–collapse strength is reduced due to an increase in dent depth as shown in Figure 8.17. If the post-collapse strength of a dented tubular is to be established numerically it is important that the computer program used has the ability to model the growth in dent depth – this would require an advanced non-linear program and powerful computing facilities.

Combined bending and dent damage

The value of D/t has an influence on the ultimate residual strength of a tubular member suffering from dent damage, as shown in Figure 8.18.

As the level of dent damage increases, the residual strength becomes independent of the level of bending damage. This trend is clearly seen in the curves in Figure 8.19 for tubes with $\lambda = 0.5$ and varying D/t.

The ultimate residual strength of a damaged tubular will be further decreased if lateral loading is present (eg wave load or buoyancy load). The curves in Figure 8.20 show that a linear interaction formula is conservative for stocky tubes and slightly non-conservative for slender tubes.

8.2.5 Fatigue behaviour of damaged tubulars

The fatigue behaviour of tubular braces which have suffered denting and bending is the subject of a current study being sponsored by the Department of Energy. Although the study has only recently commenced, initial findings show a substantial reduction in fatigue life occurs when a tubular is dented and bent. Thus, although the static behaviour of damaged tubulars is now well defined, their fatigue behaviour could provide the limiting condition in assessing the resulting integrity of the jacket.

8.2.6 Suggested method for defect assessment after collision damage

The information presented in this section can be used to establish the integrity of a steel jacket which, as the result of a collision, has a damaged (but not severed) compression member.

The methods described have been concerned with establishing the residual strength of an isolated member having pinned or clamped ends. In order to perform a jacket defect assessment it is necessary to incorporate the behaviour of the damaged tubular into the computer model of the complete jacket structure. Ideally, the special techniques which have been developed to perform mathematical modelling of damaged tubulars[8.4, 8.9] could be incorporated in jacket analysis computer programs. However, until such developments take place the following is proposed:

1. Assume that the damaged brace acts primarily as a compression member with local wave or buoyancy load providing a lateral loading. This assumption is generally true for bracing members in a triangulated jacket structure.
2. Perform a linear static jacket analysis for the following load cases, with the damaged member completely removed:
   a. storm environmental and topside dead loads
   b. self-equilibrating unit forces acting on the end nodes of the missing damaged member. These forces model the effect of a unit value of compression from the missing member on the remainder of the jacket.
3. If the member and punching shear utilisations are less than unity for Load case a. then the jacket's structural integrity is not compromised by assuming the damaged member has no residual strength. If this is the case then no repair or further inspection of the member is necessary. However, as the loads in the jacket members may be redistributed due to a reduction in the damaged member's stiffness, an analysis should be conducted to re-appraise the fatigue performance of the jacket.
4. If the member or joint utilisations exceed unity then the actual residual strength and stiffness of the damaged member should be established. This can be achieved by an elasto-plastic large-displacement analysis of the isolated member as described in References 8.4 and 8.9. In order to obtain the depth of the dent and/or the maximum deflection due to bending, a detailed survey of the damaged member would be required. The bending deflection could be measured by using a taut wire for reference while the dent depth could be measured with the aid of a template.
5. Having found the axial load/deflection characteristics of the damaged member, a non-linear compatibility equation can be solved to obtain the value of axial compression. The equation has the form:

$$e(P) = d_1 - Pd_2 \qquad (8)$$

where $e(P)$ is the non-linear relationship between the axial compression, P, and the axial shortening, e, of the damaged member

d_1 is the shortening of the line connecting the nodes of the remove member due to Load case a.

d_2 is the extension of the line connecting the nodes of the removed member due to Load case b.

6. The axial compression carried by the damaged member can then be included in the jacket model by linearly combining the displacement from Load case a. with P times the displacements from Load case b. The jacket member and joint utilisations are then computed for this new load combination. If the utilisations are greater than unity then an immediate repair will be required to ensure the integrity of the jacket. If the utilisations are less than unity then the immediate integrity of the jacket is assured. However, due to the poor fatigue behaviour of damaged members this situation may only be temporary.

This procedure is illustrated in Case Study 4 referred to in Section 8.6.

8.3 FATIGUE CRACKS

8.3.1 Introduction

This section reviews methods for assessing the significance of fatigue cracks in offshore structures with particular reference to tubular joints. The analysis methods presented are for calculating residual fatigue lives, where the 'end of life' is reached with the attainment of a pre-defined crack size (for tubular joints this is taken to be the formation of a through-thickness crack). Premature failure may arise from unstable crack extension, and this is discussed in Section 8.4.

The standard method for calculating fatigue lives at jacket design stage is the S-N curve method, but this is inappropriate for damage assessment since it is based on fatigue data obtained from initially undamaged specimens. The calculation of residual fatigue lives must therefore be performed by the alternative approach of fracture mechanics (FM). It is useful to note that the two approaches are consistent (within certain limitations) in two key areas[8.11]:

- for constant amplitude cycling, the FM variation of fatigue life against stress range is a power law relationship; this plots as a straight line on a logarithmic scale, which is the usual form of presentation for S-N curves
- for variable amplitude stress ranges, the FM calculation is equivalent to Miner's law which is generally used with the S-N method.

It may thus be seen that, provided the same assumptions are made, similar overall fatigue lives are predicted by both the S-N and FM methods.

The starting point for a fatigue crack growth analysis is the 'crack growth model'. It has three main components:

- *the crack growth law* – the simplest and most widely used law is Paris' equation
- *the crack growth constants* – these are controlled by environmental conditions and other factors and are particular to the crack growth law for which they have been derived
- *the stress intensity factor solution.*

A number of advanced crack growth models have been developed which can give accurate results under laboratory conditions. For real tubular joints in seawater the situation is more complex and there are a number of factors which are imperfectly understood, including:

- crack initiation – governed by the size of welding defects and the surface profile
- effect of seawater properties
- effect of electrochemical variables
- effect of material variables (mechanical properties, welding processes, etc)
- loading variables (frequency, R-ratio, etc).

The picture is further confused since the effects of the various parameters are often inter-related, which makes it extremely difficult to isolate the effect of any one of them. As a result, observed crack growth behaviour exhibits some randomness; very different results are obtained from nominally identical specimens. **Because of this inherent randomness, the results of analytical studies must be interpreted with caution.**

Notwithstanding these problems, it is still possible to obtain crack growth predictions which are sufficiently reliable to use as a basis for engineering decisions affecting inspection and repair.

8.3.2 The assessment of fatigue crack growth

Fatigue crack growth in steel structures is a subject which has received considerable attention from the offshore industry. In the United Kingdom, research was undertaken initially in the UKOSRP I Programme and supplemented more recently by the UKOSRP II and SERC Cohesive Fatigue Programmes. Additional data on the service performance of offshore structures in a fatigue environment have become available, and a number of high quality studies have been undertaken on specific fatigue problems by specialist consulting organisations. The net result is that the offshore industry has a fuller understanding of the behaviour of fatigue cracks in offshore structures, and is therefore better able to plan underwater inspections.

A number of introductory texts are available on fatigue fracture mechanics and it is not appropriate to include this material in here. For example, a review was published in the CIRIA UEG Guide 'Design of Tubular Joints for Offshore Structures'[(8.11)] (referred to here as the 'Design Guide'), which included data available at the time when it was written (1983). It is an indication of the speed of progress in this field that much of the earlier work has since been superseded. A brief overview of some of the more significant recent developments in fatigue research is given here. It is likely that the items described would be considered in a present-day assessment of fatigue damage (see for example the case studies referred to in Section 8.6).

Stress intensity factor solutions

The calculation methods for stress intensity factors (SIFs) reviewed in the Design Guide followed two basic approaches – the experimental approach in which the stress intensity factor for a particular case is inferred from the results of a fatigue test, and the analytical approach.

The leading experimentally based model is that developed at the London Centre for Marine Technology[(8.12)], which is based on the results of fatigue tests for T and Y joints. For the model to achieve widespread usage in the design office, it would be necessary for a large number of additional tests to be performed to enable parametric formulae for SIFs to be developed. It is significant that the most recent application of the model[(8.13)] was as a benchmark for analytical models, and it is likely that this is where the future of this approach lies.

Early analytical models were based on highly idealised geometries which were not truly representative of tubular joints. These models have generally been superseded by ones based on surface cracks in flat plates, such as the widely used Newman and Raju solution[(8.14)]. Whilst offering considerably improved accuracy, models of this type suffer from the disadvantages of not being able to account for shell curvature effects and only being able to accommodate simple stress fields (tension and bending). More powerful techniques, such as the influence function and the line spring methods, are able to overcome these deficiencies, and one such model is developed later in this section. It is significant that the more advanced models are able to utilise laboratory data on stress distributions and residual stress fields, which should act as an incentive for additional research in this area.

A more detailed review of current analytical approaches may be found in Reference 8.15.

Stress distributions

All stress intensity factor solutions rely to some degree on the stress distribution acting on the crack. Some models are dependent on the distribution through the wall thickness, others on the distribution around the joint intersection, and more advanced models depend on both. There are three main stress fields which govern fatigue crack growth (deformation stresses, notch stresses and residual stresses), as defined in Reference 8.11:

- *Deformation stresses*
  Research on deformation stresses has been governed by the requirements of S-N methods of analysis, and hence has focused on the computation of hot spot stresses. Useful progress has been made in this field, including extending the ranges of applicability of the parametric formulae[(8.16)], developing formulae for overlapping joints[(8.17)] and accounting for the effect of chord end loads on the hot spot stress[(8.18)]. However, little has been published on stress distributions, particularly through the

wall thickness, and this continues to act as a restraint on the development of FM models.

- *Notch stresses*
  Stress fields at weld toes in simple plate geometries have been studied by Lawrence and co-workers[8.19] for the purpose of developing analytical models for crack initiation. More recently, data have become available on notch stresses – for multi-planar K joints using photoelastic techniques[8.20] and for Y and K joints using strain-gauged steel specimens[8.13]. Although notch stresses have a major influence on the growth of small cracks, their effect on cracks of significant size (those which would be detected in an underwater inspection) is less important.
- *Residual stresses*
  The detrimental effect of residual stresses from welding on fatigue life was demonstrated in UKOSRP I using fillet-welded plate specimens, and this trend has recently been confirmed for welded tubular joint specimens in seawater[8.21]. Despite this, it has not been possible to incorporate residual stress effects meaningfully into FM models because of a lack of published data on residual stress levels and distributions. However, measurements of residual stresses have recently been made on three T-joints[8.22] and these will be supplemented by additional data from the next phase of the SERC Cohesive Fatigue Programme.

Environmental and related effects

Crack growth data are conventionally presented as a plot of growth rate, da/dN, versus stress intensity factor range, ΔK. The classical form for this curve is sigmoidal, with the central portion described by a power law relationship such as Paris' law (see Figure 8.21). This presentation permits ready comparisons of environmental effects.

Conventional fatigue design practice is based on S-N curves, such as the UK Department of Energy T curve[8.23], which were originally derived for tubular joints fatiguing in air. The application of these methods to joints in seawater implicitly assumes that the correct application of cathodic protection removes the problem of corrosion fatigue. Recent work undertaken in the SERC Cohesive Fatigue Programme indicates that this assumption is not valid[8.21].

It is beyond the scope of this document to perform a detailed review of this complex and still developing subject, but data for the important case of crack growth in seawater with cathodic protection have been collated and are presented in Section 5.1 of the Study Report[8.26] that led to this document. Inspection of this data leads to the important conclusion that simple crack growth laws of the Paris type are insufficient to reproduce the observed behaviour. More general, multi-term laws, are necessary[8.24], for which constants may be derived to suit the prevailing conditions.

Fatigue crack development

A major advance in the understanding of fatigue crack growth in tubular joints was marked by the development of the ACPD method (see Section 7.2.9) for measurement of crack depths[8.25]. Early data obtained with this method in the UKOSRP I Programme proved unreliable although a more consistent picture of crack development has emerged from more recent data. A screened database on crack shape development and growth characteristics is given in Section 5.1 of the Study Report[8.26] mentioned above. Realistic crack growth models should be able to reproduce this behaviour if confidence is to be placed in the computed results.

A very important régime which is frequently not addressed in tubular joint fatigue tests is crack development after the formation of through-thickness cracking. This is because the conventional definition of fatigue life (N_2) is taken to be the appearance of a through-thickness crack, on the basis that subsequent crack growth under constant amplitude loading is likely to be very rapid. However, it is known that a major change in compliance usually accompanies the development of a through-thickness crack in a tubular joint, which in a redundant structure will lead to load shedding and possibly to significant retardation of the growth rate. Since the detection of through-thickness cracks is much easier and less costly than for part-through cracks, it is likely that this régime will receive greater attention in the future.

8.3.3 Suggested method for analysing part-through cracks

There are a number of alternative approaches which may be used to model crack growth. One of the leading crack growth models, originally developed by the Southwest Research Institute (SWRI)[8.27], has been selected here as an example of a state-of-the-art model and its features are presented in some detail. Where deficiencies in the model have been highlighted by recently available research, improvements have been introduced. The improved model is implemented in the crack growth program KTUBE[8.28], which has been used for the case studies in referred to in Section 8.6.

Although the model contains procedures for the calculation of crack initiation lives as well as for the calculation of subsequent crack growth, it is the crack growth régime which is of primary interest in the context of assessing fatigue damage once discovered, since the crack initiation period has already passed. The calculation of crack initiation lives is not therefore considered here.

Crack growth law

A multi-term crack growth law has been proposed by SWRI, able to take account of the differing growth rates in the various régimes. The law is expressed as the inverse of the crack growth rate, and has the following form:

$$\frac{1}{da/dN} = \frac{1}{A_1 \Delta K^{n_1}} + \frac{1}{C \Delta K^m} - \frac{1}{C\left[(1-R)K_{IC}\right]^m} + \frac{1}{(da/dN)_p} \tag{9}$$

where R is the load ratio and is calculated from:

$$R = \frac{K_{min}}{K_{max}} \quad \text{if } K_{min} \geq 0 \tag{10a}$$

$$= 0 \quad \text{if } K_{min} \leq 0 \tag{10b}$$

C and m are material properties and usually have the same values as the constants used in the simpler Paris law – these constants govern crack growth in the lower intermediate range

A_1 and n_1 are additional material properties which define crack growth rates

K_{IC} is the plane strain fracture toughness – this property governs high crack growth rates, resulting from the intervention of static failure processes

$(da/dN)_p$ is the plateau crack growth rate, exhibited by some material/environment systems.

Values of the material properties suggested in Reference 8.27 are reproduced in Table 8.2. The crack growth characteristics derived by substituting these constants into Equation 9 are shown in Figure 8.22.

Data on fatigue crack growth in seawater with cathodic protection are presented in Section 5.1.3 of Reference 8.2.6 and it is apparent that the plateau behaviour predicted in the SWRI model has not generally been observed in laboratory tests. A modified crack growth law is therefore proposed which has the form:

$$\frac{1}{da/dN} = \frac{1}{A_1 \Delta K^{n_1}} + \frac{1}{C \Delta K^m} - \frac{1}{C\left[(1-R)K_{IC}\right]^m} + \frac{1}{A_2 \Delta K^{n_2}} - \frac{1}{A_2\left[(1-R)K_{IC}\right]^{n_2}} \tag{11}$$

The first three terms on the right hand side of this equation are identical with the corresponding terms in Equation 9, and the last two terms have been introduced to govern growth in the upper intermediate regime. The following values for the constants are proposed (in MN, m units) for crack growth in seawater for cathodically protected steel tubulars:

$A_1 = 0.125 \times 10^{-34}$
$n_1 = 32.2$
$C = 0.35 \times 10^{-13}$
$m = 5.96$
$A_2 = 0.16 \times 10^{-7}$
$n_2 = 1.395$

The crack growth law given by Equation 11 is compared with a Paris' law line in Figure 8.23.

Stress intensity factor solution

The stress intensity factor (SIF) solution proposed for use with the SWRI model is for a surface crack in a flat plate acting under tension and bending, originally proposed by Newman and Raju[8.14] (see Figure 8.24). The solution is of the form:

$$K_I = (f_t Y_t + f_b Y_b)\sqrt{(\pi a/Q)} \tag{12}$$

where $Y_t, Y_b \;=\; F(a/T, a/c, c/W, \phi)$
$Q \;=\; Q(a/C)$

Although this solution takes account of both the crack length and depth, it is not a true two-dimensional solution since the stress field must be constant in the length direction. Other limitations are that shell curvature effects are ignored and that only a linear variation of stress is permitted in the thickness direction.

An alternative approach, which overcomes the last limitation above, is to use an influence function to calculate the SIF for a crack under arbitrary loading (see Figure 8.25):

$$K_I = \int_0^a f(\eta) g(\eta, a, \text{etc})\, d\eta \tag{13}$$

where $f(\eta)$ is the stress field on the crack face
$g(\eta, a)$ is the influence function.

There are a limited number of influence function solutions available, but the Tada[8.29] solution for a finite width strip is appropriate. To account for shell curvature effects, the forces and displacements on the crack zone must be matched to those in the surrounding material; this may be achieved by the line-spring method[8.30], as demonstrated in Reference 8.31.

The major disadvantage of the combined influence function/line-spring approach is that it is strictly a one-dimensional solution, taking no account of the flaw shape. However, as an approximation, the Newman and Raju solution may be used to provide an aspect ratio correction factor, Y_a, as outlined in Reference 8.15. The aspect ratio factors for tension and bending, Y_{ta} and Y_{ba}, are plotted in Figure 8.26.

To summarise, the features of the SIF model are as follows:

- the basic SIF is calculated by an influence function method, using Tada's solution
- the effect of shell curvature is allowed for using the line-spring approach
- an approximate allowance for the flaw shape is made by use of the Newman and Raju solution.

This calculation procedure is probably the most comprehensive which may be adopted, short of a full two-dimensional crack solution, and has been used for the case studies referred to in Section 8.6.

Stress fields

The accuracy with which the stress fields acting on the crack face may be determined is often the limiting factor in the accuracy of a total analysis. It is normal to expend considerably more effort in developing the stress field for a fatigue crack growth analysis than for an S-N fatigue analysis.

Considering firstly the deformation stresses, procedures for calculating stresses on the outside surface of the chord and brace are comparatively well developed. These may be estimated by use of standard parametric SCF formulae, with assumed distribution functions[8.32] to give the variation around the joint intersection. It is, however, preferable to take account of the effect of the loading from all incoming braces and from the chord, by the influence coefficient technique. The details of this approach are given, in the case of K and Y joints, by Buitrago[8.18].

Having determined the outer fibre stress, f_o, it is necessary to estimate the variation through the wall thickness by splitting the stress into tensile and bending stresses (f_t and f_b). This may be expressed in terms of the distribution parameter, λ_s, as:

$$f_t = \lambda_s f_o \tag{14a}$$

$$f_b = (1 - \lambda_s) f_o \tag{14b}$$

It is still not common practice in the technical literature for the value of λ_s to be reported with stress analysis results or laboratory test data, and this represents a serious omission. In the case studies (see Section 8.6) it was necessary to use values of λ_s obtained from finite element studies of similar joints.

Superimposed on the deformation stresses are the notch stresses at the weld toes, and the results of the finite element work of Lawrence[8.19] can be used to estimate them. The notch stress, f_n, is given in terms of the outer surface stress, f_o, by:

$$f_n = (K_t - 1) f_o \tag{15}$$

where K_t is the notch stress concentration factor and is dependent on the ratio of the plate thickness, T, to the local weld toe radius, r, and is of the form:

$$K_t = 1 + \alpha (T/r)^{1/2} \tag{16}$$

where α has been determined by finite element studies
$= 0.35$ for $\lambda_s = 1$
$= 0.19$ for $\lambda_s = 0$

It is argued that an infinite range of radii may be found in as-welded weld profiles, and that for conservatism the value of r should be selected to give the minimum crack initiation life. The procedure for calculating r is given in Reference 8.19.

Numerical aspects of the computation procedure

The crack growth law, Equation 11, is of the form:

$$da/dN = h(\Delta K) \tag{17}$$

which may be integrated to give:

$$N_p = N(a_f) - N(a_i) = \int_{a_i}^{a_f} \frac{1}{h(\Delta K)}\, da \tag{18}$$

where a_i is the initial crack depth
a_f is the final crack depth.

The solution method proposed by SWRI is to apply a given number of cycles, say corresponding to a one-year loading period, and to compute the final crack depth, a_f, and length, c_f. This procedure is somewhat complex since Equation 18 must be solved iteratively to determine a_f.

An alternative procedure is to specify the increment in crack size, and to perform a direct integration of Equation 18 to determine the number of loading cycles. The integration must be performed numerically, and significant errors can be introduced if the integration step is too large. In the program KTUBE[8.28] an adaptive integration procedure is used, whereby the specified crack growth increment is successively sub-divided until convergence is achieved.

For a given increment in crack depth, the change in crack length may also be computed if it is assumed that the same law and crack growth constants govern crack growth in both the length and depth directions. However, with stress corrosion there may be substantial differences in crack growth conditions along the crack front, and hence the validity of this assumption is doubtful. The preferred method is therefore for the user to specify the corresponding increments in both length and depth, based on experimental data for crack shape development.

To commence the calculation, it is necessary to specify the initial crack depth. It is normal to take this as the nominal depth at crack initiation to enable the complete crack growth characteristic to be generated – this characteristic may then be entered at any crack depth to determine the residual life. Following the procedure of Chen and Lawrence[8.33] which was developed to join crack initiation and fatigue crack growth models, the initial crack size may be calculated as:

$$a_i = \frac{0.0954\sqrt{T}}{\alpha F_u^{\,0.9}} \text{ in MN, m units} \tag{19}$$

where F_u is the ultimate tensile strength of the material
α is as defined for Equation 16.

The crack growth procedure outlined above is for constant amplitude stress cycling. If variable amplitude cycling is experienced, as in offshore structures under hydrodynamic loading, it is necessary to weight the contribution to crack growth from each stress range by the relative frequency of each range. The resulting equation is:

$$da/dN = \int_0^{\infty} \left[\frac{da}{dN}(\Delta K) \right] f(\Delta K) \; d(\Delta K) \qquad (20)$$

where $f(\Delta K)$ is the probability density function for the SIF range.

Equation 20 implicitly assumes that load interaction effects do not occur.

A flowchart for the crack growth computation is given in Figure 8.27.

8.3.4 Analysis methods for through-thickness cracks

Increased interest is currently being expressed by the offshore industry in the behaviour of through-thickness cracks, since these may be detected more economically and reliably than part-through cracks. Analysis methods for such cracks are required to enable their continuing behaviour to be predicted reliably.

The situation is very complex for through-thickness cracks located at tubular joints, because of the geometry and nature of the stress fields at the intersection. The only feasible analysis technique is to use a numerical method, such as finite element analysis, in which the crack is represented in the model. Such analyses are expensive, because of the number of elements required to model the cracked joint and because a separate analysis is required for each crack length under consideration.

There are circumstances in which through-thickness cracks may occur in a tubular member remote from any joints, eg:

- through-thickness cracks which have developed from single-sided butt welds, for example at brace to stub joints or at access windows
- cracks which have developed at appurtenance supports – on early North Sea platforms these were frequently rigidly welded to the structure and have proved troublesome in fatigue, sometimes leading to a local failure.

Examples of both types of crack geometries are illustrated in Figure 8.28. For the simple circumferential crack, analytical solutions are available[8.34] which give the SIF for axial bending load acting on the member. The SIF may be expressed in the form:

$$K_I = (f_t Y_t + f_b Y_b)\sqrt{(\pi a)} \qquad (21)$$

where f_t and f_b are the tensile and bending stresses acting in the member
Y_t and Y_b are plotted in Figure 8.29.

The SIF for the tubular member rises steeply with increasing crack size. It is very unconservative to apply an SIF solution derived for an infinite plate to this geometry.

The case of cracks emanating from a circular hole has been extensively studied for flat plates[8.35]. It is generally non-conversative to idealise the hole and the adjacent edge cracks as a single crack of the same overall length, since this ignores the stress concentration caused by the presence of the hole. It is thus necessary to determine the stress field surrounding the hole in order to estimate the SIF for the edge cracks.

8.3.5 Benchmark studies

To establish confidence in the use of the crack growth model, and to gain an understanding of the sensitivity of the results to the governing parameters, a number of benchmark studies have been carried out. The variables in the studies (Analyses Nos 1–5) are listed in Table 8.3; the parameters that remained constant were:

- *R–ratio* – all studies were performed at an R–ratio of 0, using the low R–ratio crack growth constants for each environment
- *Residual stress* – a uniform tensile residual stress of 250 MN/m^2 was assumed
- *Crack shape* – the aspect ratio (ratio of crack depth to total length) was assumed to be 1/15
- *Weld toe stress concentrations* – the weld toe stress fields recommended by Lawrence[8.19] were used; the constants are reported in Table 8.4

- *Initial crack sizes* – the procedure for calculating the initial crack size proposed by Chen and Lawrence[8.33] was used; sizes for various plate thicknesses are given in Table 8.5.

The results of the benchmark studies were:

- *Crack growth in air*
  Analysis No 2 was used to verify the calculation procedure against an experimentally derived design S-N curve for joints with the same wall thickness (16 mm). The results for Analysis No 2, in Figure 8.30, generally show very good agreement. The computed break point in the curve occurs close to 10^7 cycles, which is in agreement with the design curve. At lives beyond 10^7 cycles the FM analysis predicts a smaller negative slope for the S-N curve than the widely used design value (of –1/5). This value is, however, known to be a conservative approximation to actual behaviour in the threshold régime.
- *Effect of stress distribution factor, λ_s*
  A comparison between Analyses Nos 2 and 3, for which $\lambda_s = 0.15$ and 1.0 respectively, is shown in the form of S-N curves in Figure 8.30 and as crack growth characteristics in Figure 8.31. For a given hot spot stress range, increasing λ_s causes a substantial reduction in the fatigue life. Significantly, a high value of λ_s makes the crack much more difficult to detect since the crack is at an inspectable size for a much lower proportion of its total life.
- *Effect of wall thickness*
  The effect of wall thickness is demonstrated by comparing the results of Analyses Nos 1 and 2 in Figure 8.32. The expected reduction in fatigue life for greater thickness can be seen and close agreement is obtained with the appropriate S-N curves.
- *Effect of environment*
  The effect of environment on fatigue life is shown in Figure 8.33 with a comparison of Analyses Nos 2, 4 and 5. The comparison between the air environment and freely corroding seawater conditions is as expected, with a reduction in the fatigue life in seawater. The S-N curve for seawater with cathodic protection is unusual, with a reduction in life at higher stress ranges and a very significant increase at lower stress ranges. These comparisons, reported in terms of the total life, are disproportionately affected by the life spent as a small crack. Plotting out the crack growth characteristic against the residual life (Figure 8.34) shows that the behaviour of cracks of finite size is less sensitive to the surrounding environment. This is an important conclusion since underwater inspections are aimed at detecting cracks of this size.

8.4 CRACK STABILITY

8.4.1 Introduction

This section reviews methods of assessing the stability of cracks in steel structures – methods where the objective is to determine, for a given crack size, the load that will cause unstable crack extension (ie fracture). Stability assessments frequently need to be conducted in conjunction with fatigue crack growth studies.

Calculations on crack stability, in common with fatigue crack growth calculations, rely on fracture mechanics techniques but the emphasis of the two analysis procedures is rather different in several respects. Firstly, unstable crack extension is generally preceded by yielding in the crack zone, and this should be accounted for in the analysis. Secondly, the number of load cases to be considered in a stability assessment is generally much reduced, so it may be possible to devote greater effort to the analysis of each crack size/load case combination.

There are a number of areas of difficulty associated with the assessment of crack stability, including the following:

- the complexity of the analysis problem – necessitating either very powerful analysis techniques or the introduction of simplifying assumptions
- the development and interpretation of toughness data for the steel, both in the welded and unwelded conditions
- lack of data on residual stresses
- the diversity of approach of the commonly used assessment procedures.

An additional problem is that, unlike fatigue crack growth, test results are not available from large-scale specimens of representative geometries. There is thus no effective benchmarking of stability analyses for cracks located in complex geometries, such as tubular joints. It is therefore prudent to utilise conservative assessment procedures.

If good quality steels have been used in the construction, and if the structure is well-designed so that the stress levels are moderate, it may be possible to demonstrate conclusively that adequate defect tolerance exists. Assessment results will be less definitive in other cases, even if the actual risk of crack instability is low, because of the inherent conservatism of the assessment procedures. In these cases engineering judgement must be exercised in the interpretation of the results, and consideration should also be given to the consequences of failure.

8.4.2 General background

Overview

The failure of flawed structures under tension is governed by two separate, though inter-related, processes:

- crack extension (fracture)
- plastic collapse.

A fundamental aspect of any assessment procedure is the manner in which the two failure mechanisms are handled. The simplest approach is to treat each mechanism separately for the purposes of the analysis and to link the two mechanisms by a failure interaction equation. This approach may be typified by the CEGB R6 method[8.36]. The alternative strategy is to perform a rigorous analysis of crack stability, making full allowance for plasticity as appropriate. In such an analysis, the calculated crack driving force will automatically tend to infinity as plastic collapse approaches, and hence failure will be correctly predicted.

It is generally accepted that there are three basic régimes which govern crack extension:

- *linear elastic behaviour*, which governs brittle failure
- *elastic-plastic behaviour*, associated with ductile failure
- *tearing behaviour.*

In the linear elastic and elastic-plastic régimes, failure is generally defined as the point at which crack 'initiation' occurs, where in this context initiation means the onset of crack growth under static loading.

The tearing régime is concerned with the behaviour of the crack after initiation. Although often appropriate in the nuclear industry, the types of steels and the service temperatures in the offshore industry severely limit the applicability of tearing stability methods, and they will not be considered further here.

For both the linear elastic and the elastic-plastic régimes the criterion for failure is of the following form:

$$\text{crack driving force parameter} \geq \text{material resistance parameter} \qquad (22)$$

In the linear elastic case the crack driving force is characterised by the stress intensity factor (K_I) and the material resistance by the plane strain fracture toughness (K_{IC}). However, steels with good low temperature properties (ie those commonly used in the offshore industry) generally preclude true brittle failure, and linear elastic methods are therefore of secondary interest.

In the elastic-plastic régime the crack driving force and the material resistance may be characterised by the crack tip opening displacement (CTOD) or the J-integral. These two quantities are somewhat interchangeable although CTOD is much more widely used in the offshore industry because of the availability of material property data. An important difference compared with the linear elastic regime is that the crack driving force is not proportional to the load; it typically varies with the square of the load.

Basic analytical approaches

The most widely used analytical methods are linear elastic techniques which have been derived to compute stress intensity factors. A number of compendia of solutions and analytical techniques are available which enable SIFs to be computed for a wide range of geometries and loading conditions – a review of these may be found in Reference 8.11.

The SIF is of limited use in crack stability calculations because fracture is generally preceded by significant yielding in the high toughness/low yield stress steels commonly encountered in the offshore industry. The role of plasticity in the behaviour of cracks has been investigated in a number of detailed analytical studies performed using non-linear finite element analysis[8.37].

An important conclusion of this work was the fundamental difference in behaviour between 'contained' and 'uncontained' plasticity. Contained plasticity typically occurs around short cracks, with the plastic zone not extending to any of the free surfaces of the body, except possibly breaking back to the faces of the crack. This typically occurs with cracks in localised stress concentrations, such as at fillet welds. Provided that the crack is small, the plastic zone may remain contained even for applied stress levels approaching general yield. For uncontained plasticity, the plastic zone extends across the full width of the body at the cracked section, and marks the onset of plastic collapse. An example of each, for an internally pressurised cylinder, is shown in Figure 8.35. A greatly increased crack diving force accompanies the onset of uncontained plasticity.

Provided that the plasticity is contained, the stress fields surrounding the crack are not greatly affected by the presence of the plasticity, and linear elastic methods of analysis remain valid, with some modifications. The most usual modification is simply to increase the effective crack size by means of a plastic zone correction[8.38]; this procedure has been found to be effective for applied stresses up to approximately 80% of yield, although this is dependent on the geometry and the material properties.

An alternative approach or performing an approximate analysis of crack tip plasticity is the Dugdale strip yield model[8.39]. In theory this model is only applicable to cases where limited yielding occurs, but it has been found that the solution can perform well at load levels approaching plastic collapse.

A major advantage of analysis methods which depend on modifications of linear elastic techniques is that the wide range of available elastic crack tip solutions may be used. These analysis methods are generally both easy to use and sufficiently powerful to handle complexities such as non-uniform stress fields and arbitary crack geometries.

When uncontained plasticity occurs, true elastic-plastic analysis methods should be used. It is of course possible to undertake a non-linear finite element analysis for the geometry under consideration, although this is likely to be prohibitively expensive particularly since a separate analysis must generally be performed for each load case. However, for certain simple geometries the results of parametric studies are available and enable the crack driving force to be read from tables of results[8.40]. The geometries studied include cracks in tubular members and pipelines, and cracks in plated structures (deck girders, etc), but do not include more complex configurations like tubular joints. Whilst the range of geometries studied to date is somewhat restrictive, it is anticipated that this range will be extended in due course.

By far the most widely used analysis method for use in practical situations is design curves. The most important of these is the CTOD design curve[8.41, 8.42], reproduced here in Figure 8.36, which computes the applied CTOD from the strain acting in the crack location, calculated for the uncracked body. This curve is closely paralleled by the less widely used J-design curve[8.43].

The major advantage of design curves is their inherent simplicity and ease of use. However, by virtue of their simplicity they are unable to cater adequately for the full range of problems encountered, and the resultant factor of safety is variable. A number of criticisms have been levelled against the CTOD design curve, of which perhaps the most serious are that plastic collapse is inadequately treated and that little guidance is offered on computing the strains for use in the design curve equations. Several proposals[8.44, 8.45] have recently been made to overcome these major failings, and it is likely that these proposed modifications will achieve official status in due course.

An alternative design curve approach is the CEGB R6 method[8.36], which takes the form of an interaction diagram for failure arising from either fracture or plastic collapse (see Figure 8.37). Whilst this method overcomes most of the criticisms afflicting other design curves, its applicability in the offshore industry is undermined because the fracture criterion is expressed in terms of the plane strain fracture toughness, for which there are comparatively little test data available. An equivalent curve, utilising CTOD as the parameter to characterise fracture, has been proposed by Anderson and co-workers[8.45].

A number of studies[8.46, 8.47] have been performed to compare the relative performances of the most widely used design curves. On the basis of a careful comparison between the CTOD design curve and the CEGB R6 methods, Reference 8.47 arrived at the following conclusions:

- The R6 method developed well-behaved solutions with narrow scatter bands. The solutions were conservative in all cases.
- The CTOD design curve developed solutions with a wide scatter. A number of these solutions were unconservative, particularly at high applied stress levels.
- The performance of the CTOD design curve could be improved very significantly by making use of the actual stress-strain curve of the material and by taking proper account of the geometry and the actual loading on the crack.

Design curve assessment procedures will continue to be used for the foreseeable future because of the practical advantages in their application. Although methods of improving their accuracy have been identified, it nonetheless remains essential to include an adequate factor of safety within the procedures to cover all possible applications. This may be unsatisfactory for certain situations where a large factor of safety is not required and it is therefore likely that multi-level assessment procedures will become more popular. In these a design curve would be used initially to give a simple, conservative, assessment of defects but more advanced methods would be used for critical applications or where greater accuracy was required.

8.4.3 Material property behaviour

In an assessment of crack stability in steel structures a knowledge of the materials properties of the components under examination is essential. The type of data needed is dependent on the analysis being carried out.

For the CTOD-based approach, both the CTOD value, δ, and the yield strength F_y are required. When determining the toughness, the material can exhibit different behaviour with the following toughness classification:

- δ_c – crack tip opening displacement at either unstable fracture or at the onset of an arrested brittle crack when there is no evidence to suggest that slow crack growth has occurred
- δ_i – crack tip opening displacement at which slow crack growth commences
- δ_m – crack tip opening displacement at first attainment of maximum load plateau
- δ_u – crack opening displacement at either unstable fracture or onset of arrested brittle crack, or pop-in where there is evidence to suggest that slow crack growth has occurred.

These types of behaviour are illustrated in Figure 8.38 and can be thought of in terms of a measure of the degree of ductility of the material. The behaviour is dependent on the inherent nature of the material (which is a factor of chemical composition, heat treatment, steelmaking practice, etc) and also on the temperature of testing. For offshore steels at the temperature of interest (–10°C), δ_c and, to a limited extent, δ_u values generally occur.

As discussed in the previous section, the CTOD approach is only applicable to cases where limited yielding occurs. Where a material exhibits a high degree of stable and ductile crack extension, use of the δ_u or δ_m value can lead to unconservative assessments. To maintain conservatism the selection of the critical CTOD should be limited to that at the crack initiation, ie δ_c or δ_i rather than that at the maximum load for highly ductile materials which can develop extensive stable tearing before crack instability. This suggests that a limitation of applicability of the CTOD design curve method can be directly related to the capability of a material for ductile tearing before crack instability. For most of the steels used in the North Sea the amount of stable cracking before instability will be limited, and on the whole the CTOD concept will remain applicable at the temperature of interest (–10°C to +4°C) provided that the value of crack initiation is used and appropriate steps are taken to maintain conservatism as outlined in the previous section.

However, although a method for determining the initiation value δ_i is outlined in BS 5762[8.48], in reality it is often difficult to determine this on the load trace and the specimen. An alternative method for predicting this stage is to construct the materials resistance curve, R[8.49]. In essence, the R-curve is a graphical representation of the variation in crack growth resistance during the process of stable crack initiation but also provides information at the point of crack initiation. It is directly compatible with tearing stability analyses and is likely to become more important as offshore steels improve in quality in the future.

For an R6 analysis, the crack initiation stress intensity factor, K_{IC}, and the flow stress are required. The latter is usually taken as the average of yield and tensile strength for work hardening materials. For other analyses, such as J-integral or the WI Level 2 method (see Section 8.4.4) the material's resistance can be measured either as a J-integral or again the CTOD toughness. However it should be noted that the material's stress-strain curve is required for satisfactory assignment of correct Ramberg-Osgood parameters although it is believed that a good assessment of these is possible from knowledge of the yield strength, tensile strength and elongation to fracture.

As discussed in Section 5.2 of the Study Report[8.26] that led to this document, the most generally available fracture data available are in the form of Charpy impact data; they are rarely available as CTOD or K_{IC} toughness. In the absence of the most suitable toughness data for crack stability assessment, the Charpy impact values have to be transformed into suitable toughness data at the temperature of interest via transition curves and suitable correlations. The first stage of transformation, ie obtaining Charpy values at the temperature of interest is discussed in Reference 8.26. The following section provides a means of correlating the impact data to fracture toughness and illustrates the conservatism of the correlations with two examples.

Correlation of Charpy impact data with fracture toughness data

Although a correlation relating Charpy impact energy to CTOD toughness is essentially what is required to obtain the appropriate material fracture resistance, δ_c, for crack stability calculations, correlations of parent plate and HAZ toughness have not been attempted because Charpy impact requirements for steels have generally been derived from large-scale wide-plate fracture initiation tests and correlations of the smaller initiation test (CTOD) with Charpy impact values have not been required. CTOD toughness has generally therefore only been measured for welding procedure qualification, for comparison of effect of varying welding procedure techniques on toughness and for engineering critical assessments where CTOD toughness is the most suitable material property input parameter.

For weld metals, the situation is slightly different in that few wide plate tests have been carried out and attempts at CTOD/Charpy correlations have been made[8.50, 8.51].

Although direct comparisons do not exist for HAZ and parent plate, empirical correlations of impact toughness to the plane strain fracture toughness, K_{IC}, do exist[8.52] and have been subject to review[8.53]. Of the correlations in existence, a number are shown to be conservative with respect to measured K_{IC} values of Grade 50D steel having a Charpy transition curve similar to many of the steels used in the North Sea (see Figure 8.39). The correlations marked 5 and 9 in the figure (and due to Rolfe and Novak[8.54] and Sailors and Corten[8.55]) are those most appropriate for consideration here as they have been derived from impact data in the transition range and have the largest databases. Of the two, the Sailors and Corten relationship gives the more conservative approach except at impact energies less than 19 J, but as the Rolfe and Novak correlation has been derived from a greater number of steels and includes steels of similar strength to those used in the North Sea it is concluded that this is the most appropriate correlation to use.

Having converted the toughness data from an impact value to a linear elastic fracture mechanics value, it is then necessary to replace this by the elastic-plastic fracture resistance, CTOD, as appropriate to the crack stability assessment being carried out. For this, the analysis of Ingham and Harrison[8.56] proves particularly useful. In a study of the various methods of determining defect acceptance, they attempted to correlate on the basis of experimental relationships between K_{IC} (upper shelf initiation toughness) and CTOD at temperatures corresponding to upper shelf and upper transition conditions, and between K_{IC} and CTOD for lower shelf and lower transition conditions. Their results gave the following relationships:

Upper shelf temperatures ($T \geq 10°C$)

$$\delta = \frac{K_{JC}^2(1-\upsilon^2)}{1.5EF_f} \qquad \text{where } F_f = \frac{F_y + F_u}{2} \tag{23}$$

Upper transition region ($-4°C \leq T \leq +24°C$)

$$\delta = \frac{nK_{JC}^2(1-\upsilon^2)}{mEF_y} \tag{24}$$

Lower transition region ($-73°C \le T \le -4°C$)

$$\delta = \frac{nK_{IC}^{2}(1-\upsilon^{2})}{mEF_{y}} \tag{25}$$

Lower shelf temperatures ($T \le -73°C$)

$$\delta = \frac{K_{IC}^{2}(1-\upsilon^{2})}{2F_{y}E} \tag{26}$$

where m and n are experimentally derived constants.

Equations 24 and 25, applicable to the transition range, are essentially the same – the only difference being the measured value of fracture toughness, either K_{JC} the elastic-plastic fracture toughness or K_{IC} the plane strain fracture toughness, and the value of M (where $M = m/n$) applicable for the temperature range in question. As the correlation of Charpy toughness to fracture toughness is based on linear elastic determinations, it is appropriate to use Equation 25 where the measured values of m and n give a value of M between 1.73 and 1.87 depending on temperature.

The lower figure is applicable to the upper end of the temperature range, ie towards –4°C, and therefore it is considered appropriate to use a value of 1.75 in determining the CTOD levels of the steels in common use in the North Sea and maintain a continuing level of conservatism.

Thus the following conversion procedure is recommended to produce a CTOD toughness level for each area of a component/joint of interest.

- Determine the average Charpy impact toughness for the component/joint in question from available mill sheets.
- By use of Charpy transition curves, relate this to impact toughness at 0°C or –10°C, whichever is appropriate.
- Convert Charpy impact toughness, CV, to linear elastic fracture toughness using the Rolfe and Novak correlation:

$$\frac{K_{IC}^{2}}{E} = 0.22CV^{1.5} \tag{27}$$

- Convert K_{IC} value to elastic plastic fracture toughness, δ, using the following relationship:

$$\delta = \frac{K_{IC}^{2}(1-\upsilon^{2})}{MF_{y}E}$$

where F_y is the appropriate value of yield stress.

Examples of conversions

1. Table 8.6 gives some data on Grade 50D steel provided by the Welding Institute[8.57] for both Charpy testing and CTOD testing. By taking the minimum recorded Charpy value at –50°C of 21 J and using the above conversions:

$$\frac{K_{IC}^{2}}{E} = 0.22CV^{1.5} = 0.22 \times 21^{1.5} = 21.17$$

$$\delta_c = \frac{K_{IC}^{2}}{E}\,\frac{1-\upsilon^{2}}{Mf_y} \quad \text{where m} = 1.75$$

$$= \frac{21.17 \times 0.91}{1.75 \times 410} = 0.027 \text{ mm}$$

The result is that a CTOD toughness of 0.027 mm is obtained for a temperature of –50°C via the above conversion route. The minimum toughness recorded in CTOD tests in the table for the same material at –78°C was 0.049 mm. Thus a safety factor of 1.81 was introduced by the conversion in addition to the extra conservatism introduced by the difference in test temperature.

2. For the heat affected zone of steel welded by the submerged arc process, the following measurements are available[8.58]:

- Charpy toughness 41 J

- CTOD toughness 0.130 mm
- yield strength 425 N/mm^2
- test temperature –40°C

The conversion procedure gives a CTOD toughness of 0.071 mm, ie a safety factor of 1.84 over the measured value above.

3. Similarly, measured data from MMA welding on Grade 50D steel show(8.59):
   - Charpy toughness at upper shelf temperature 76.3 J and yield strength 400 N/mm^2
   - CTOD toughness at upper shelf temperature 0.37 mm and yield strength 550 N/mm^2

Using Equation 25, the CTOD toughness corresponding to a Charpy toughness of 76.3 J is 0.19 mm, giving a safety factor of 1.95 over the measured value of 0.37 mm. However, the measured values are upper shelf values and using Equation 23 (appropriate to the upper shelf) the Charpy toughness converts to the slightly lower CTOD value of 0.18 mm.

These examples indicate that the conservatism introduced by this method of deriving an appropriate CTOD toughness is quite high, with a safety factor of just under 2 being common. However, due to uncertainties in data and areas of applicability for the conversions, it is felt that this degree of conservatism is appropriate.

8.4.4 Benchmark studies

A simple benchmark study on crack stability has been performed to demonstrate the use of some of the stability assessment methods outlined in this section. The three methods selected have been chosen because of their ease of use or their accuracy. The CTOD design curve is not one of them – because of its inherent limitations and because it is, in its present form, likely to be superseded in the near future.

The problem selected, which has also been analysed in Reference 8.47, is a tubular member with an internal circumferential crack loaded in tension. This geometry would be representative of a tubular member or a pipeline with a crack developing from a circumferential butt weld. Details of the problem are shown in Figure 8.40 and the material properties are presented in Table 8.7. The stress-strain characteristics, which have been idealised as a Ramberg-Osgood material, are plotted in Figure 8.41.

In these benchmark studies, the definition of failure is based on the initiation of crack extension, which may be expressed as:

$$\delta_{app} = \delta_c \tag{28}$$

where δ_{app} is the applied CTOD
δ_c is the CTOD at the onset of crack extension.

Plastic zone corrected elastic solution

The stress intensity factor for an internally cracked cylinder under axial tensile stress, f_t, is:

$$K_I = f_t\sqrt{(\pi a)}Y_t(R_i/R_o,\ a/t) \tag{29}$$

where the function $Y_t(R_i/R_o, a/t)$ is given in graphical format in Figure 8.42.

The plane strain plastic zone correction is calculated as follows. The crack tip plastic zone size is approximately:

$$r_y = \frac{K_I^2}{6\pi F_y^2} \tag{30}$$

When a plastic zone has formed, the effective crack size becomes:

$$a_{eff} = a + r_y \tag{31}$$

The effective crack size, a_{eff}, is substituted for in Equation 29 and K_I is recomputed. It may be seen that the new value of K_I will affect the size of the plastic zone, and it is thus necessary to iterate Equations 29 to 31 – convergence is normally achieved in 2–5 iterations. Finally, the CTOD toughness may be calculated from the stress intensity factor, as:

$$\delta_{app} = \frac{4}{\pi}\frac{K_I^2}{E'F_y} \tag{32}$$

where E' = the effective modulus
= E for plane stress
= $E/(1-\upsilon^2)$ for plane strain.

The calculated CTOD is shown, together with the results from the other two studies, in Figure 8.43. Although the computed CTOD is accurate at stress levels up to 250 N/mm^2, which is approximately 80% of general yield, beyond this level CTOD is underpredicted (as expected from the known behaviour of this analytical model). A separate calculation should be performed to check for plastic collapse at the cracked section, which in this case governs failure.

Elastic–plastic finite element solution

In parametric studies on various cracked geometries carried out by the EPRI[8.39] the crack driving force, expressed in terms of the J-integral, is computed from the equation:

$$J = g(a_{eff};\ R_i/R_o)\frac{f^2}{E'} + \alpha(F_y^2/E)(T-a)\,h(a/T;\ n;\ R_i/R_o)(f/F_y)^{n+1} \tag{33}$$

$$= J_{ep} + J_p \tag{34}$$

where g and h are functions computed in Reference 8.39
a_{eff} is as defined in Equation 31
α and n are constants in the Ramberg-Osgood material model.

The equation has two terms, which correspond to the elastic-plastic and the fully plastic regimes. At low load levels the first term is the more important and the second becomes dominant at high load levels. The second term scales with the applied load level raised to a power dependent on the work hardening properties of the material. This feature, which leads to a great simplification of the form of the solution, is a result of the use of the Ramberg-Osgood material model.

To convert Equation 33 to CTOD toughness, the following should be used:

$$\delta_{app} = \frac{4}{\pi}\frac{J_{ep}}{F_y} + d_n\frac{J_p}{F_y} \tag{35}$$

where d_n is a conversion factor dependent on the material properties (= 0.55 in the present case).

The predicted CTOD from this model is also plotted in Figure 8.43. Because the analysis technique takes full account of the plastic response, the computed CTOD becomes large as plastic collapse is approached. At lower load levels, the results are close to those predicted by the simpler modified elastic solution described earlier.

The Welding Institute Level 2 method

As part of a comprehensive review of methods to overcome the inherent weaknesses of the CTOD design curve, as presented in PD 6493[8.42], the Welding Institute have recently proposed a three-level assessment procedure[8.44]. The level of the procedure to be used in a given case would depend on the importance of and the stress levels in the structure under examination. The Level 2 procedure, which is intended to combine accuracy with simplicity of use, calculates the applied CTOD from the following equation:

$$\delta_{app} = \frac{\pi F_y a}{E}\left\{\frac{f_p}{f_n}\left[\frac{8}{\pi}\ \ln\sec\left(\frac{\pi}{2}\frac{f_n}{F_y}\right)\right]^{1/2} + \frac{f_s}{F_y}\right\}^2 \tag{36}$$

where f_p and f_s are the effective primary and secondary stresses, as defined in Reference 8.44.
f_n is the net section stress, defined for this geometry as:

$$f_n = \frac{f_t}{1-a/T} \tag{37}$$

Equation 36 is derived from the expression for the CTOD in a centre-cracked panel under tension. The value of the equation becomes very large as the quotient f_n/F_Y tends to unity, which represents the onset of plastic collapse. This test for plastic collapse is conservative, since the actual collapse load is generally higher owing to constraint and work hardening. It is also known that under conditions of high bending stress, as at the hot spot of a tubular joint, the collapse of the remaining ligament at a cracked section will be restricted by the general continuity of the structure[8.46].

Although derived originally for a very simple geometry and loading condition, Equation 36 is extended to other more complex cases by means of the calculation procedure for the effective primary and secondary stresses, f_p and f_s.

The calculated CTOD is again shown in Figure 8.43. Generally good agreement is noted with the other models at stress levels up to 250 N/mm^2 but, at the nominal collapse stress (320 N/mm^2), the crack driving force tends to infinity.

Results from the studies

The results of these benchmark studies are compared in the form of a stability diagram, Figure 8.43, in which the failure load is given by the intersection point between the crack driving force curve and the toughness line. The results graphically illustrate the interaction between crack stability and plastic collapse; because of the high toughness level in the steel ($\delta_c = 0.93$ mm), plastic collapse governs failure. Methods which do not specifically address plastic collapse do not perform well in this régime, but may be more satisfactory when applied to the lower toughness materials commonly found in weldments.

The Welding Institute Level 2 model is conservative in its treatment of plastic collapse – a simple improvement in this respect would be to substitute the flow stress for the yield stress in Equation 36 to give a better estimate of the collapse load. The handling of plastic collapse is likely to be excessively conservative for bending loads where restraint is provided by the remainder of the structure.

A summary of the applicability of the three methods investigated is given in Table 8.8. For design purposes, it would be necessary to apply a factor of safety to the load to prevent fracture from occurring. Its magnitude would depend on a number of considerations, including the consequences of failure and the forewarning of imminent failure, but it would normally not be less than 1.5.

8.5 ASSESSMENT OF STRUCTURAL REDUNDANCY

Structural redundancy plays a major role in determining an optimised inspection plan. The classification of a member or joint as 'fracture critical' or 'non-fracture critical' is largely dependent on the redundancy of the structure.

It is potentially very costly and time consuming to investigate redundancy in a jacket-type structure, and therefore the method used for classifying the components should be carefully considered.

The basic method for establishing structural redundancy is to sever the member being investigated and to re-run a linear-elastic static strength analysis for the jacket. A more rigorous method would involve analysing the jacket, with the severed member, by an elastoplastic static strength analysis. This is more rigorous since members adjacent to the severed member may become plastic and, in turn, cause a secondary distribution of loads in the jacket. In the limit, this secondary distribution could lead to progressive collapse of the jacket due to formation of a mechanism.

The complexity and cost of a large non-linear analysis should not be underestimated. An operator with experience of ultimate load studies on a southern North Sea gas platform has quoted computer run times more than a hundred times those for an elastic analysis. From the technical standpoint, whilst elastic-plastic beam theory is reasonably well established and can give good answers for simple geometries, the non-linear behaviour of tubular joints is considerably more complex. At the present time a full non-linear analysis cannot be considered a realistic alternative, except for small structures where the degree of non-linearity is low.

If a linear analysis is performed, the method of establishing whether the loss of a member will lead to the consequential failure of other members depends on the design code used. The best method is to use a limit state design code and to check the remaining structure against the ultimate limit state. If a permissible stress design code is being used, then unity ratios greater than FOS (where FOS is the nominal factor of safety for the design code) may be taken as a conservative check for failure.

Even with a linear analysis it can become very expensive to investigate redundancy because of the number of analyses required (one per severed member). Economies should be effected whenever possible, and the following measures may be employed:

- *Structural model*
  The structural model should be trimmed back to the main structure. Appurtenances should only be included, as non-structural members, for the purpose of calculating the wave loading.
- *Substructuring*
  Maximum use should be made of the substructuring facilities available within the analysis program. By adopting this approach, only the substructure containing the severed member needs to be reanalysed. A sensible division for a jacket structure is to use one substructure per framing level, giving a total of 6–9 substructures for a typical northern North Sea structure. Savings may be made in the model size by locating the connection models at the framing levels rather than by introducing new nodes mid-way between the framing levels. Further savings may also be made by restricting the back-substitution to the substructure being examined, and to the substructures immediately above and below this level. If an elastoplastic analysis is to be performed, the non-linear behaviour can be restricted to the substructures adjacent to the severed member, with the remaining substructure having linearly elastic behaviour.
- *Load cases*
  A minimum number of load cases should be analysed. The environmental loading should be based on the maximum base shear position for the storm wave (with current and wind as appropriate) acting in four directions at 45° spacing. For a linear analysis, the results for the reverse wave directions can be obtained by superposition of load cases at the post-processing stage. In a non-linear analysis, however, eight separate wave directions would be required.
- *Structural symmetry*
  Maximum use should be made of structural symmetry to minimise the number of members to be investigated.

In a recent desk study on a northern North Sea structure, it was estimated that some 80 analyses would be required to investigate redundancy in the primary structure. It was considered that this number would have given a relatively thorough investigation of the redundancy, and that some of the members included could have been eliminated by a manual appraisal of their function.

The methodology outlined will cover the cases where a clean break occurs in a brace member, such as at a brace/stub connection. Failures occurring at a tubular joint are more complex and some possibilities are shown in Figure 8.44. The footprint failure in particular, which could result from either fatigue or ship impact loadings, causes a significant weakening of the chord member, and this should be taken into account in the redundancy check. Attention is also drawn to the potentially dangerous case of fatigue cracks developing from the crown position at a joint if the chord is a tensile member, since chord failure could result.

8.6 CASE STUDIES

Four examples of the techniques described in this Section are to be found in Appendix 3 of the Study Report(8.26) that led to this document:

- *Example 1* shows the procedure required to compute fatigue crack growth characteristics for a circumferential crack at the chord side weld toe in a ring stiffened tubular joint.
- *Example 2* shows the procedure required to compute fatigue crack growth characteristics for a longitudinal crack at the chord side weld toe in a simple tubular joint.
- *Example 3* shows the assessment procedure for crack stability of a longitudinal part-through crack in a simple tubular joint.
- *Example 4* shows the procedure to assess the effect of a damaged member on the utilisation of adjacent members. This procedure is illustrated by investigating the consequences of a damaged member on a small jacket structure.

Table 8.1: *Properties of damaged members illustrated in Figures 8.1 and 8.2*

Example	A	B
D (mm)	356	406
t (mm)	12.7	12.7
L (mm)	13,904	12,450
F_y (N/mm²)	355	235
d (mm)	40.3	78
x (mm)	9635	7644
u (mm)	127	110
U (N.mm)	6.6×10^7	5.6×10^7

d = dent depth
x = location of dent from member end
u = displacement at location
U = estimate of energy involved in the collision

Table 8.2: *Suggested constants for the SWRI crack growth law*

Crack growth environment	Constants in Equation 9						
	A_1	C	n_1	m	K_{IC}	R	$(da/dN)_o$
Air Low R	0.53×10^{-29}	0.4×10^{-11}	32.0	3.15	250	0.2	(0.0)
Air High R	1.0×10^{-14}	1.1×10^{-11}	13.3	3.15	250	0.5	(0.0)
Seawater Free corrosion potential Low R	0.53×10^{-20}	0.303×10^{-11}	17.5	3.65	250	0.2	(0.0)
Seawater Free corrosion potential Low R	1.1×10^{-14}	0.59×10^{-11}	13.3	3.65	250	0.5	(0.0)
Seawater Cathodic polarisation Low R	0.125×10^{-34}	0.34×10^{-13}	32.0	5.93	250	0.2	1.0×10^{-6}
Seawater Cathodic polarisation High R	Insufficient experimental data to determine constants						

Units are MN and m
(From Reference 8.27)

Table 8.3: *The benchmark studies of Section 8.3.5*

Analysis No	Chord size (mm)	λ	Environment
1	914×32	0.15	Air
2	457×16	0.15	Air
3	457×16	1.0	Air
4	457×16	0.15	Seawater, freely corroding
5	457×16	0.15	Seawater, cathodic polarisation

Table 8.4: *Values of notch stress concentration factor, K_t, for weld toe stress concentrations for Grade 50D steel*

Plate thickness (mm)	K_t	
	Membrane tension	Bending
16	3.65	2.44
25.4	4.33	2.81
32	4.74	3.03
38.1	5.08	3.22
50.8	5.71	3.56
63.5	6.27	3.86
82.55	7.01	4.26
101.6	7.67	4.62
107.95	7.67	4.73

Weld toe stress field is of the form(8.24) $f_n = f_o (K_t - 1) \exp[-35(K_t - 1)a/T]$

Table 8.5: *Initial crack depths for fatigue crack studies for Grade 50D steel*

Plate thickness (mm)	Initial crack depth (mm)	
	Membrane tension	Bending
16	0.12	0.22
25.4	0.15	0.28
32	0.17	0.31
38.1	0.18	0.34
50.8	0.21	0.39
63.5	0.24	0.44
82.55	0.27	0.50
101.60	0.30	0.56
107.95	0.31	0.57

(From Reference 8.33)

Table 8.6: *Measured Charpy V notch impact toughness and CTOD toughness for Grade 50D steel*

	Charpy impact toughness *CV* (J)	CTOD toughness δ_c (mm)	Yield strength F_y (N/mm²)
Measured values	71	0.099	410
Measured values	21	0.049	
		0.147	
		0.127	
		0.057	
		0.221	
Temperature (°C)	–50	–78	–70

(From Reference 8.57)

Table 8.7: *Benchmark studies – material properties*

Property	Value
Young's modulus, E	207,000 N/mm^2
Yield strength, F_y	366 N/mm^2
Ultimate strength, F_u	557 N/mm^2
Poisson's ratio, υ	0.3
Critical CTOD, δ_c	0.93 mm
Ramberg-Osgood coefficients:	
Constant, α	1.35
Exponent, n	7.0

Table 8.8: *Benchmark studies – applicability of the three methods*

Analysis method	Steel toughness			
	Low δ_c/F_y steel		High δ_c/F_y steel	
	Stress régime		Stress régime	
	Bending	Tension	Bending	Tension
Plastic zone corrected elastic solution	Yes	Yes	No(1)	No
The Welding Institute Level 2 model	Yes	Yes	Yes(2)	Yes
Elastic-plastic finite element solution	Yes	Yes	Yes	Yes

1 *May give acceptable answers if adequate restraint provided by continuity with the remainder of the structure*

2 *Excessively conservative if restraint provided by continuity with the remainder of the structure*

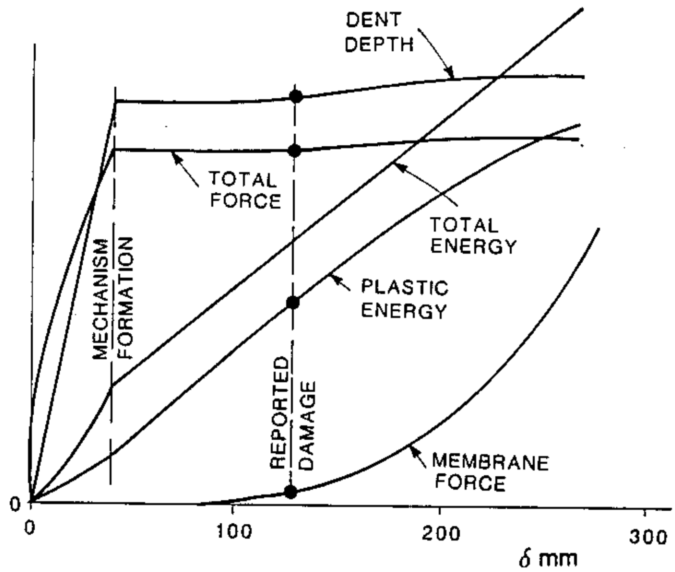


Figure 8.1: *Damage history – Example A*
(From Reference 8.1)

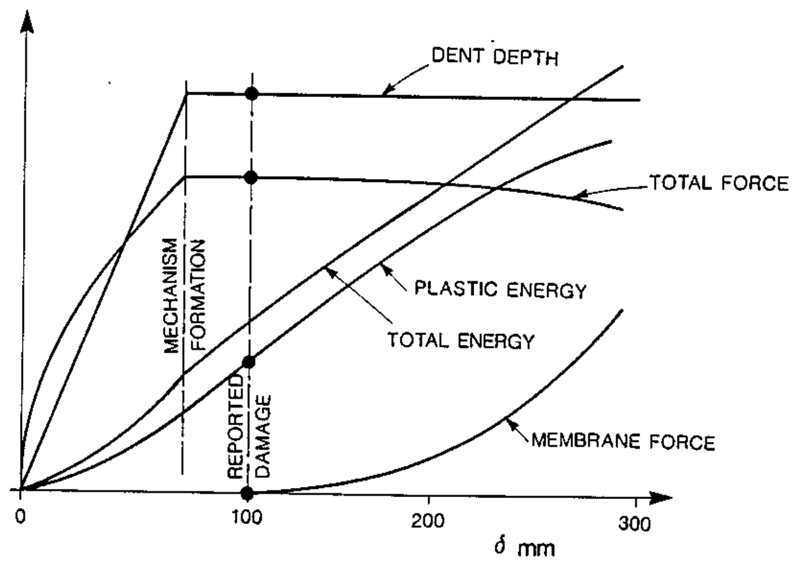


Figure 8.2: *Damage history – Example B*
(From Reference 8.1)

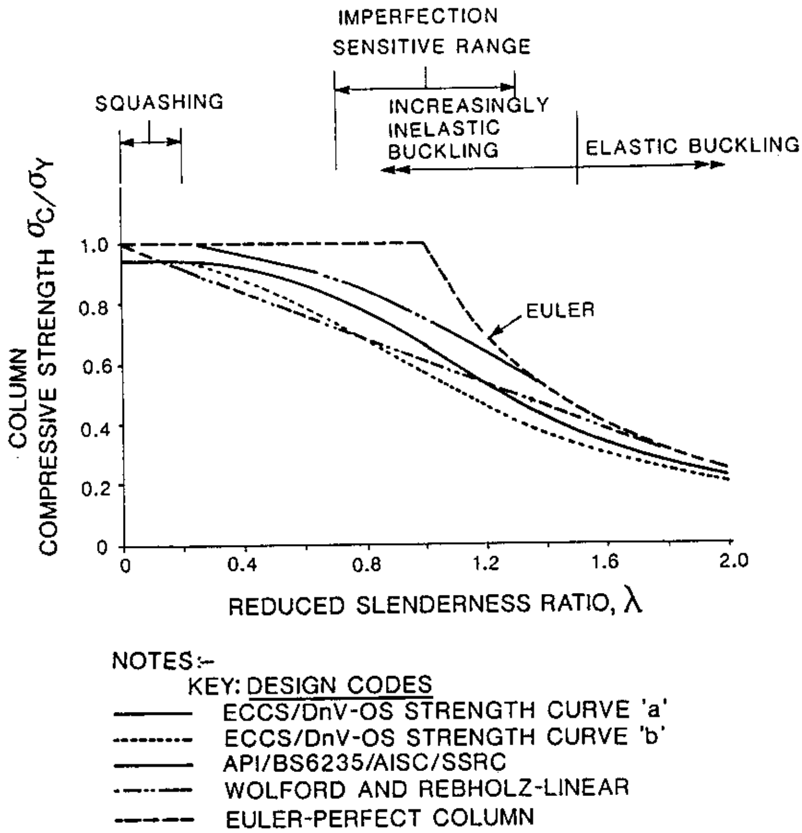


Figure 8.3: *Effect of reduced slenderness ratio on column compressive strength (From Reference 8.10)*

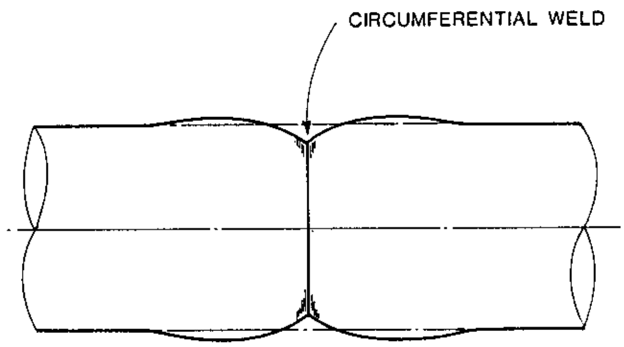


Figure 8.4: *Bulge-type imperfections introduced by circumferential welds (From Reference 8.10)*

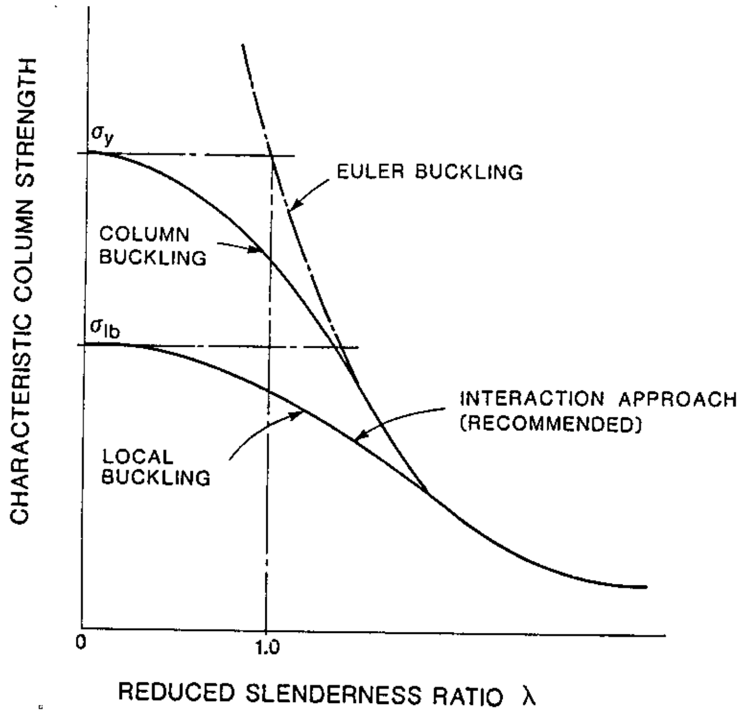


Figure 8.5: *Illustration of interaction between column and local buckling*
(From Reference 8.10)

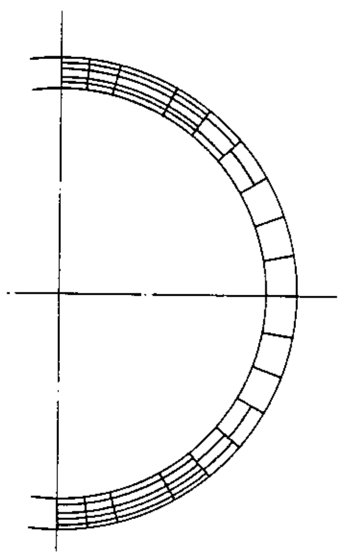


Figure 8.6: *Sub-division of cross-section into 'fibres'*
(From Reference 8.4)

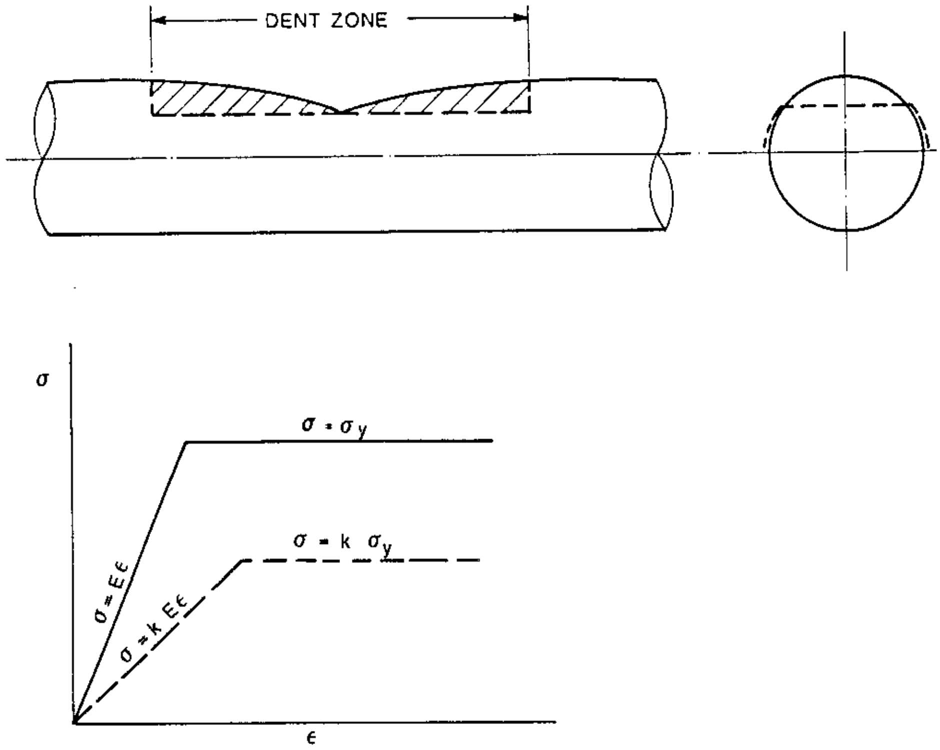


Figure 8.7: *Numerical characterization of dents*
(From Reference 8.7)

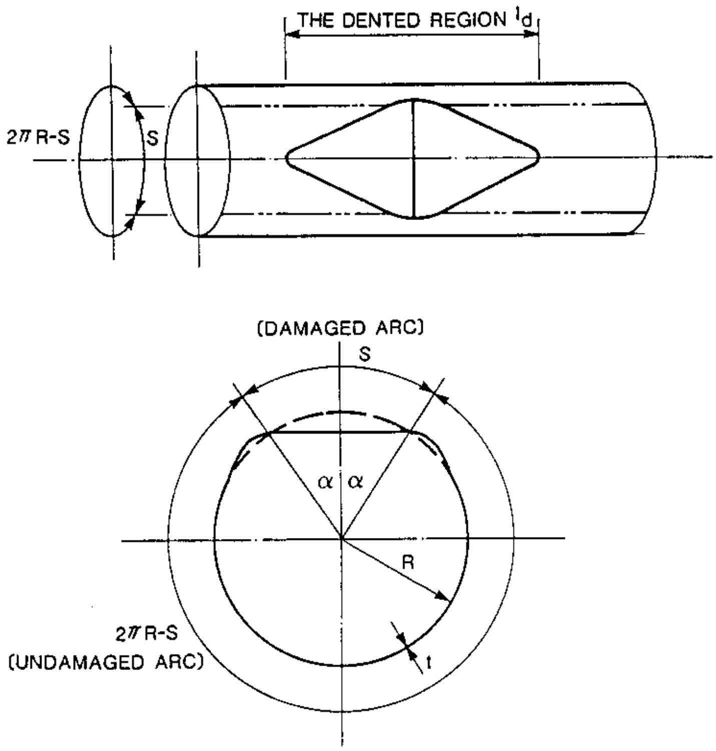


Figure 8.8: *Idealization of a sharp dent*
(From Reference 8.9)

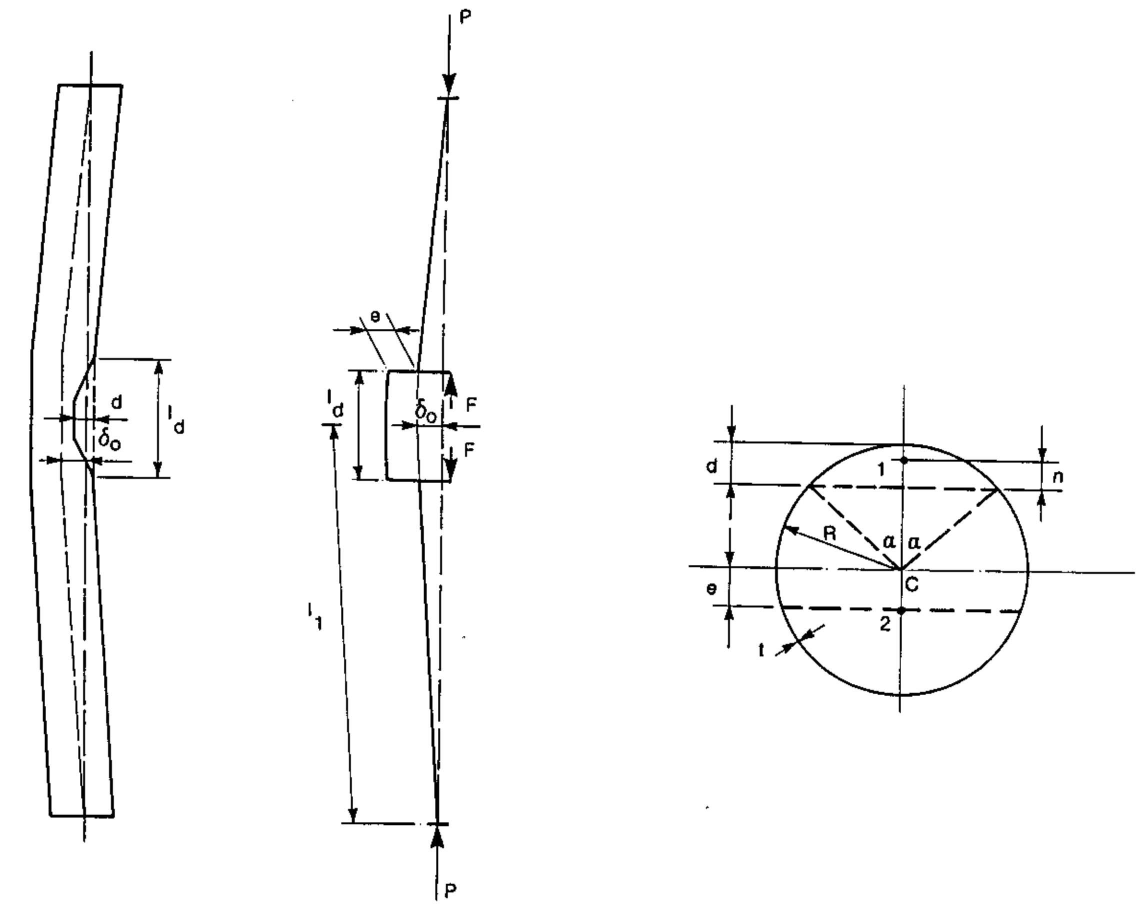


Figure 8.9: *Dent damage theoretical model*
(From Reference 8.9)

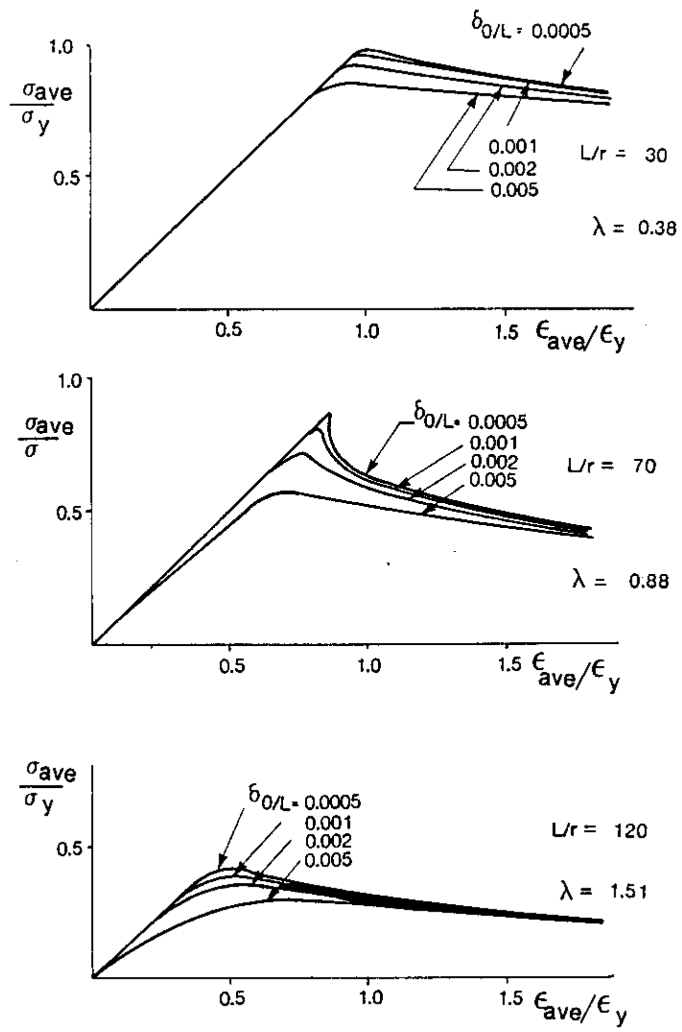


Figure 8.10: *Effect of the slenderness, λ, of a simply supported damaged tubular on its residual strength*
(From Reference 8.4)

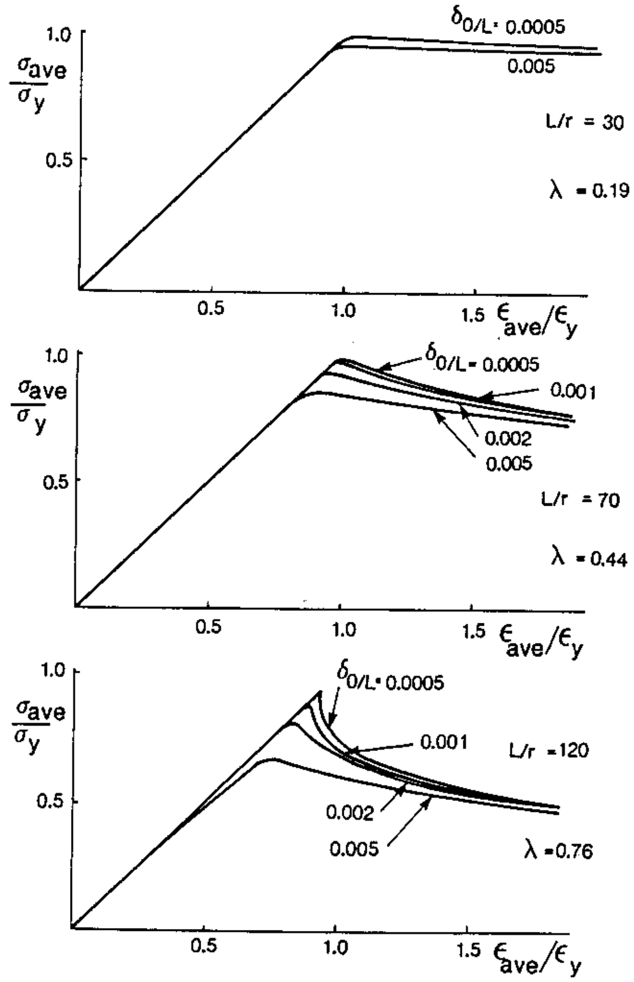


Figure 8.11: *Effect of the slenderness, λ, of a clamped damaged tubular on its residual strength (From Reference 8.4)*

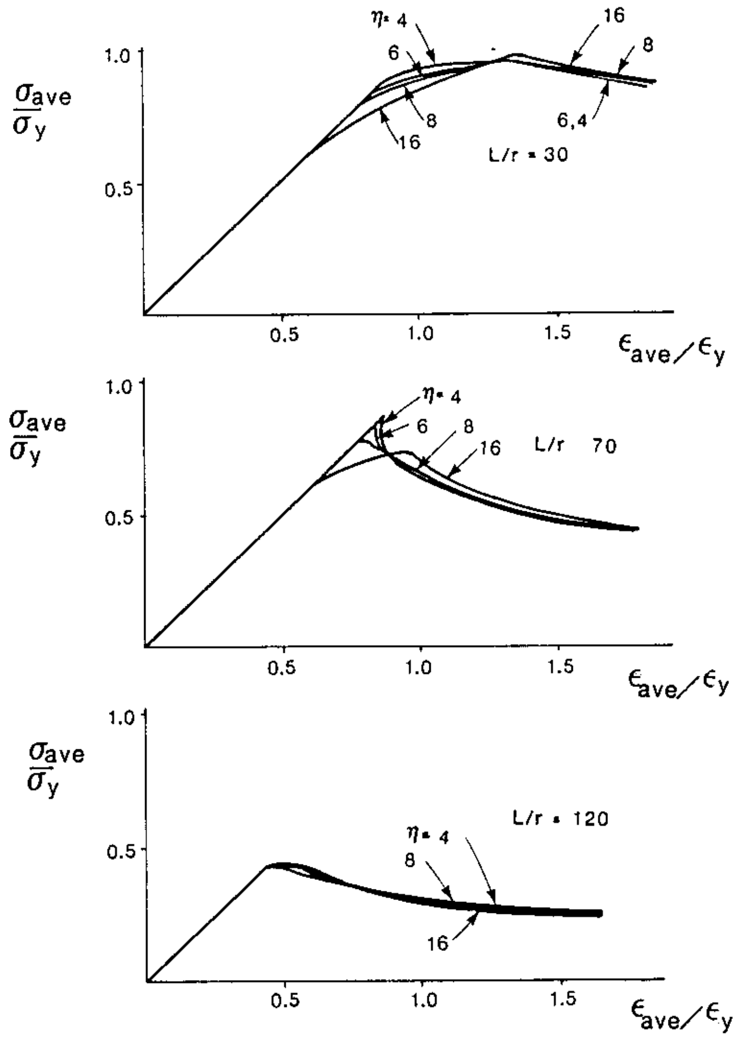


Figure 8.12: *Effect of weld-induced residual stress on load-shortening curves for simply supported tubes*
(From Reference 8.12)

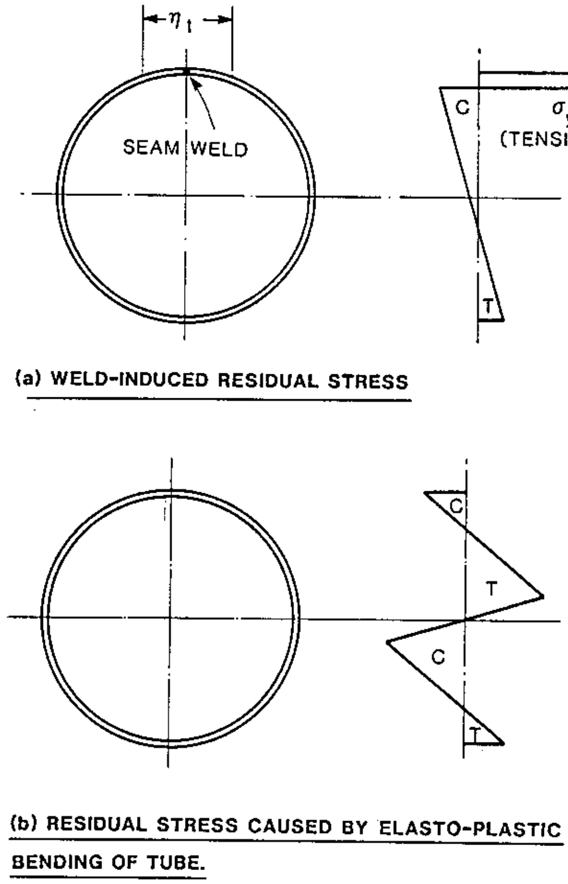


Figure 8.13: *Residual stress distributions*
(From Reference 8.4)

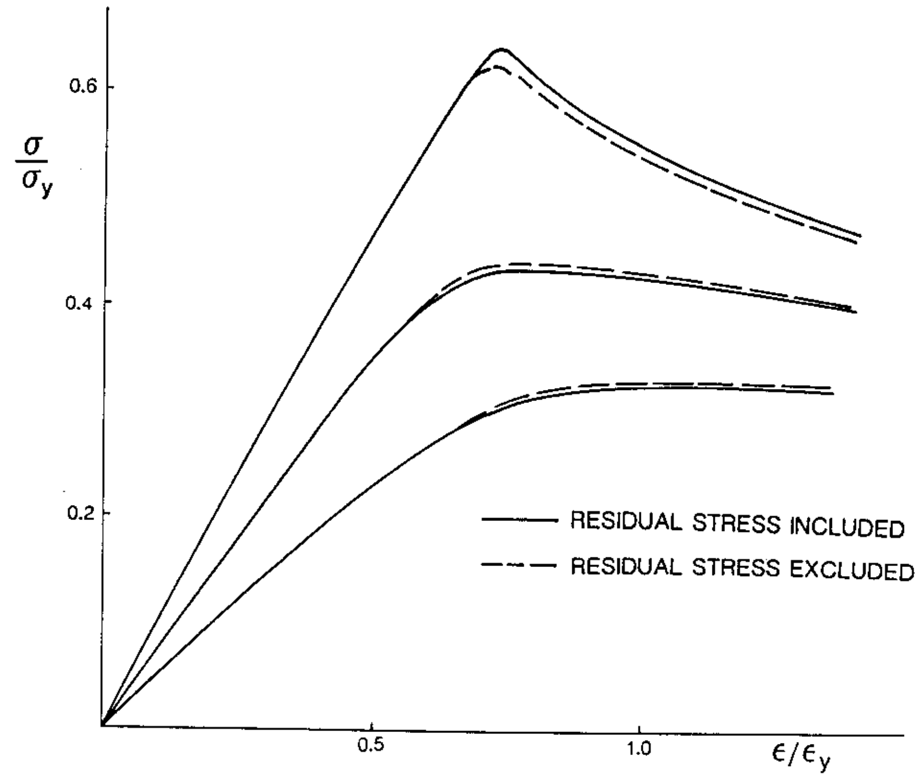


Figure 8.14: *Contribution of residual stress to damage effect*
Simply supported tubes, L/r = 70
(From Reference 8.5)

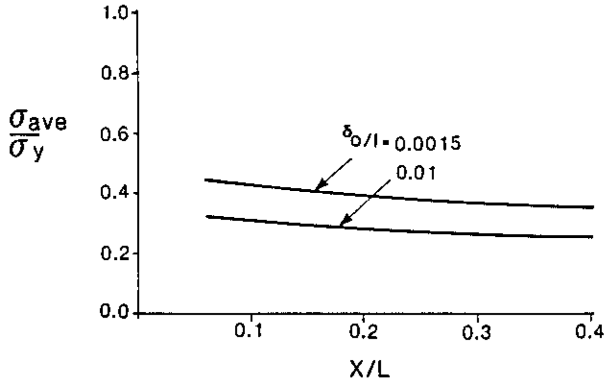


Figure 8.15(a): *Effect of length of dent on ultimate load of a damaged tubular*

Dent at mid-span $\lambda = 0.7$ $D = 100$ mm $t = 2.0$ mm
$\sigma_y = 360$ N/mm^2 $E = 210{,}000$ N/mm^2 $d/D = 0.15$
(From Reference 8.9)

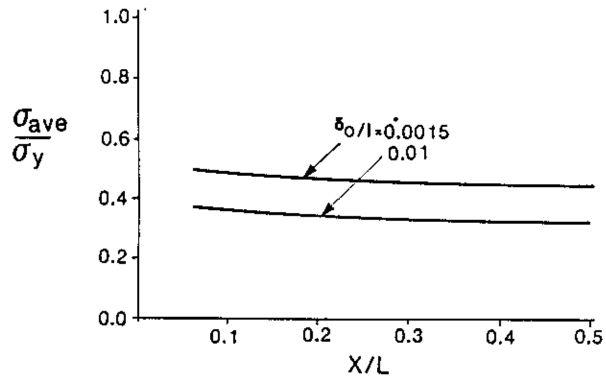


Figure 8.15(b): *Effect of location of dent on ultimate load of a damaged tubular*

$\lambda = 0.7$ $D = 100$ mm $t = 2.0$ mm $\sigma_y = 360$ N/mm^2
$E = 210{,}000$ N/mm^2 $d/D = 0.15$ sharp dent
(From Reference 8.9)

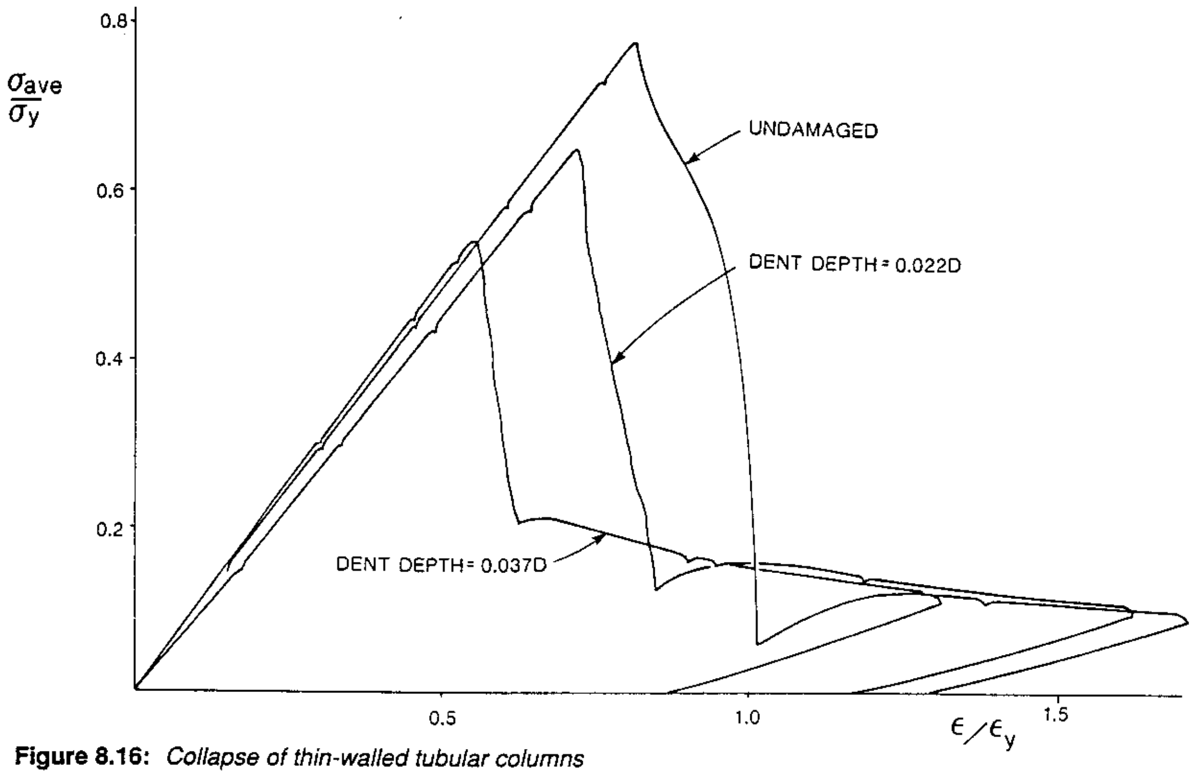


Figure 8.16: *Collapse of thin-walled tubular columns*
(From Reference 8.5)

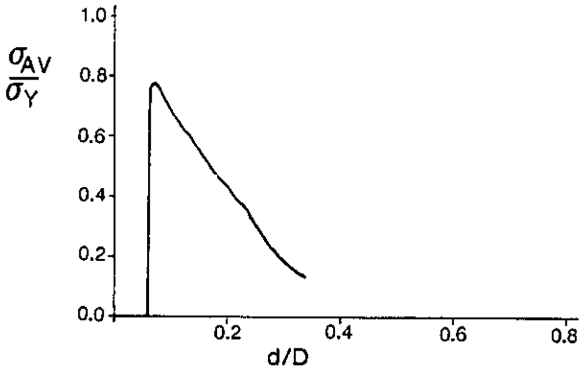


Figure 8.17: *Growth of dent depth as a function of axial load*
Determined experimentally (see Reference 8.9)

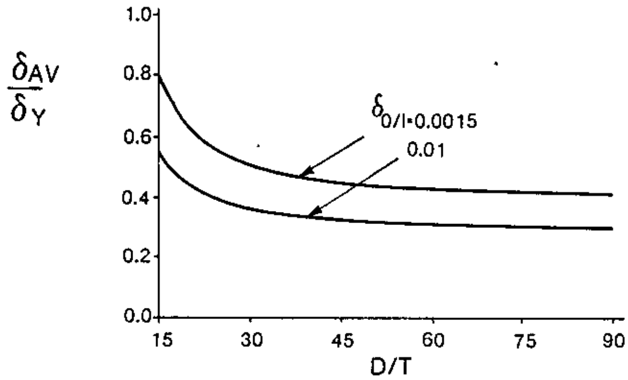


Figure 8.18: *Ultimate load of a dented tubular member as a function of D/t ratio*
$\lambda = 0.7$ D = 100 mm $\sigma_y = 360$ N/mm²
E = 210,000 N/mm² d/D = 0.15 dent at mid-span
(From Reference 8.9)

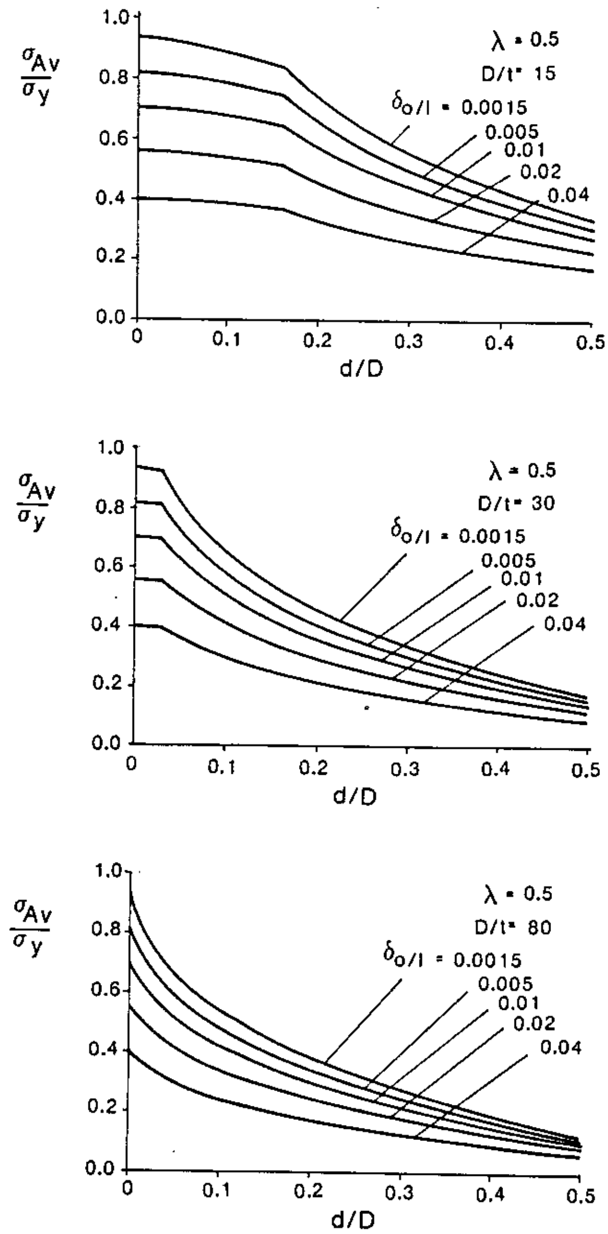


Figure 8.19: *Ultimate load of a dented tubular member as a function of the depth of the dent (From Reference 8.9)*

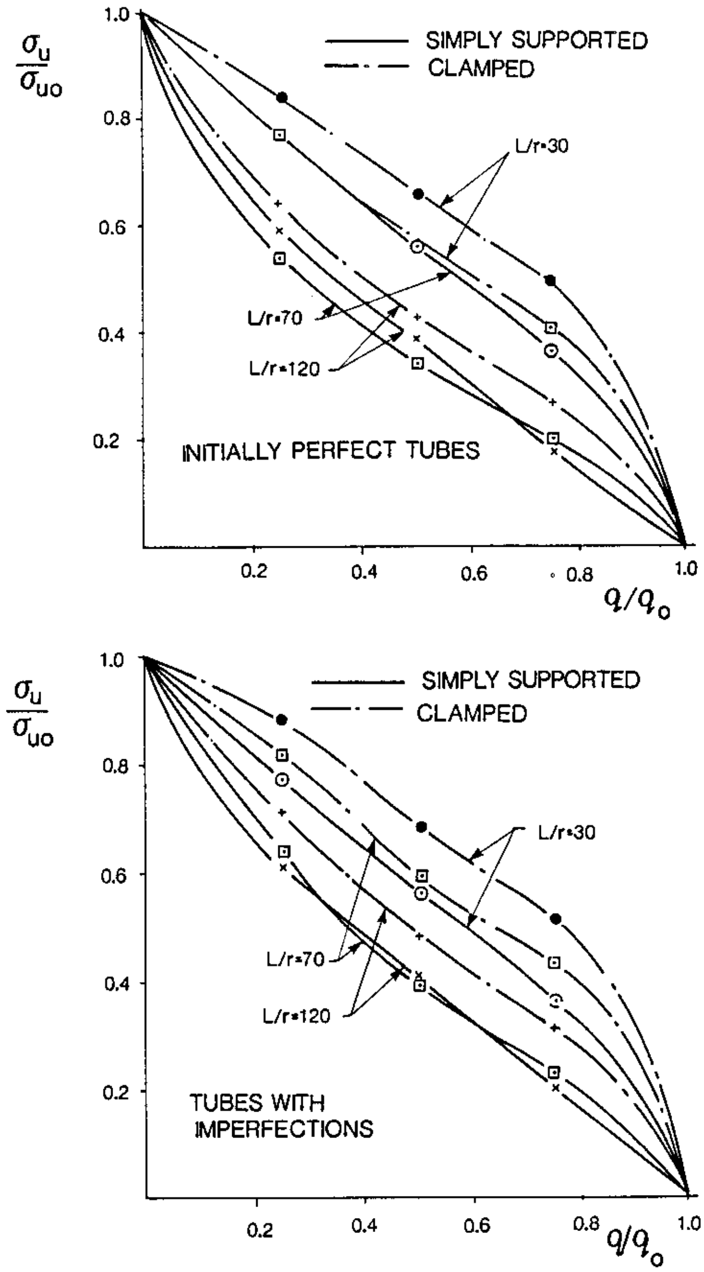


Figure 8.20: *Effect of uniform lateral load-interaction curves*
(From Reference 8.5)

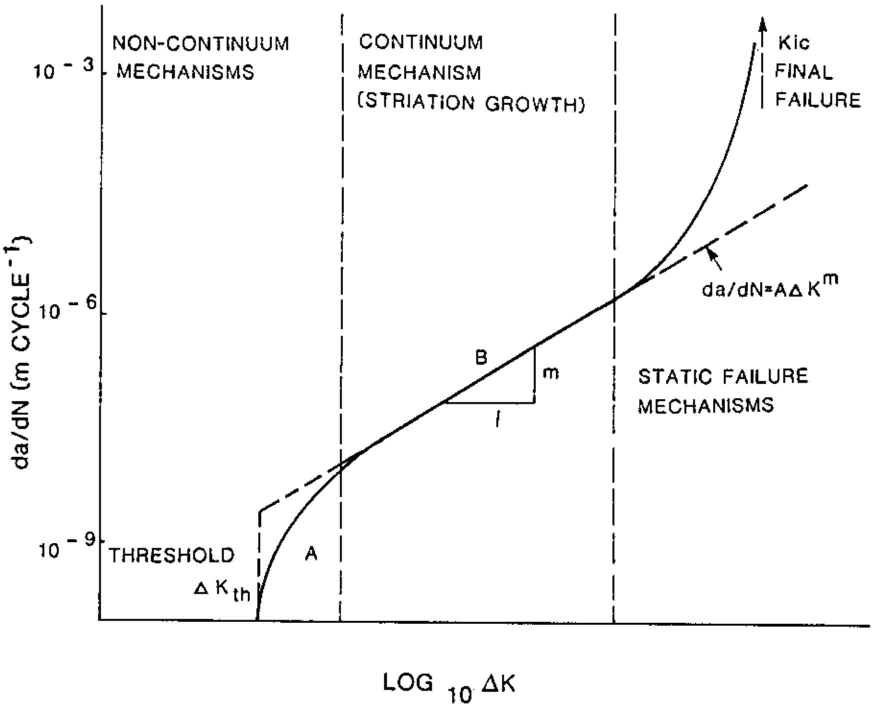


Figure 8.21: *Schematic presentation of crack growth*

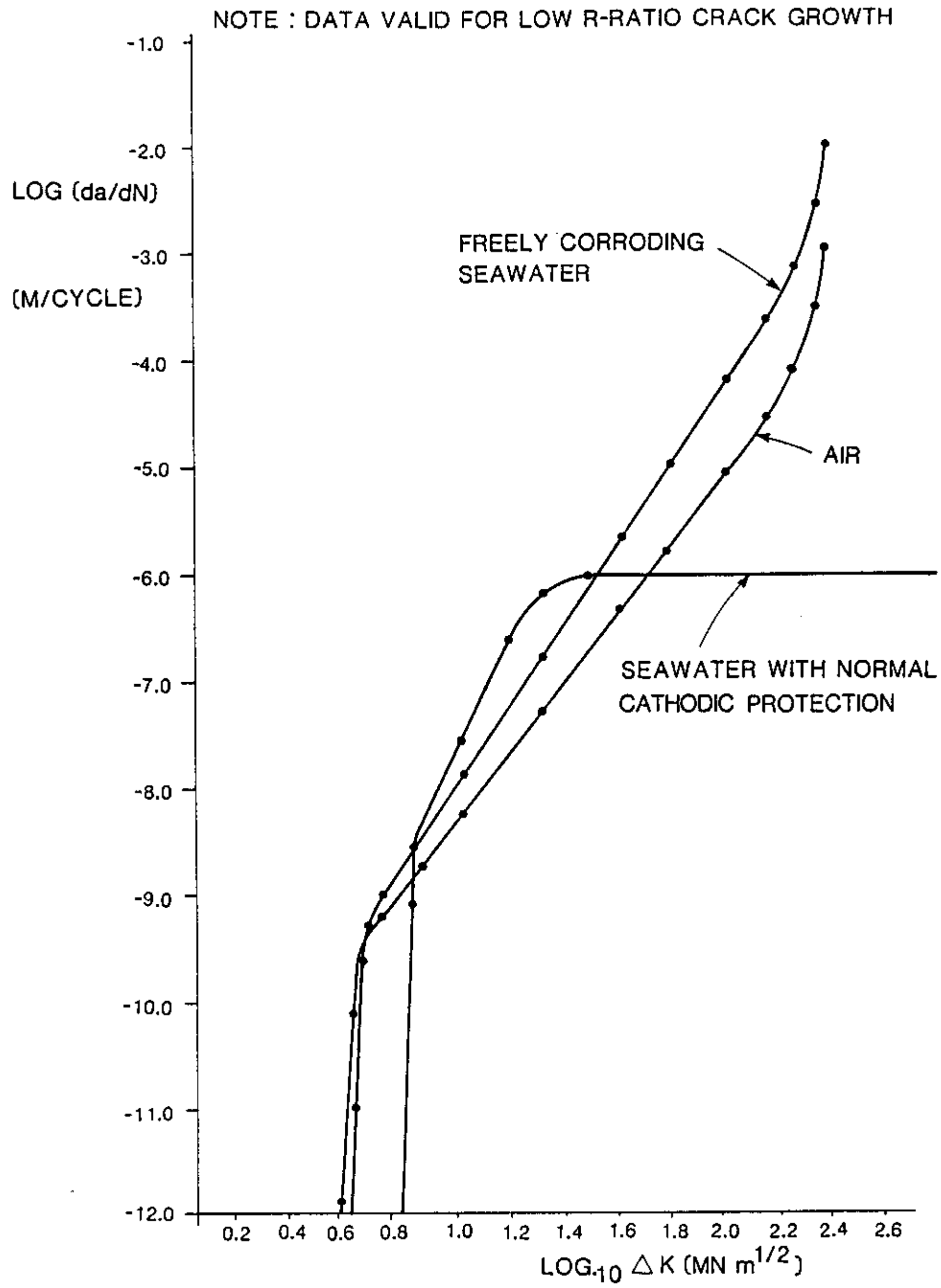


Figure 8.22: *SWRI crack growth law for different environments*

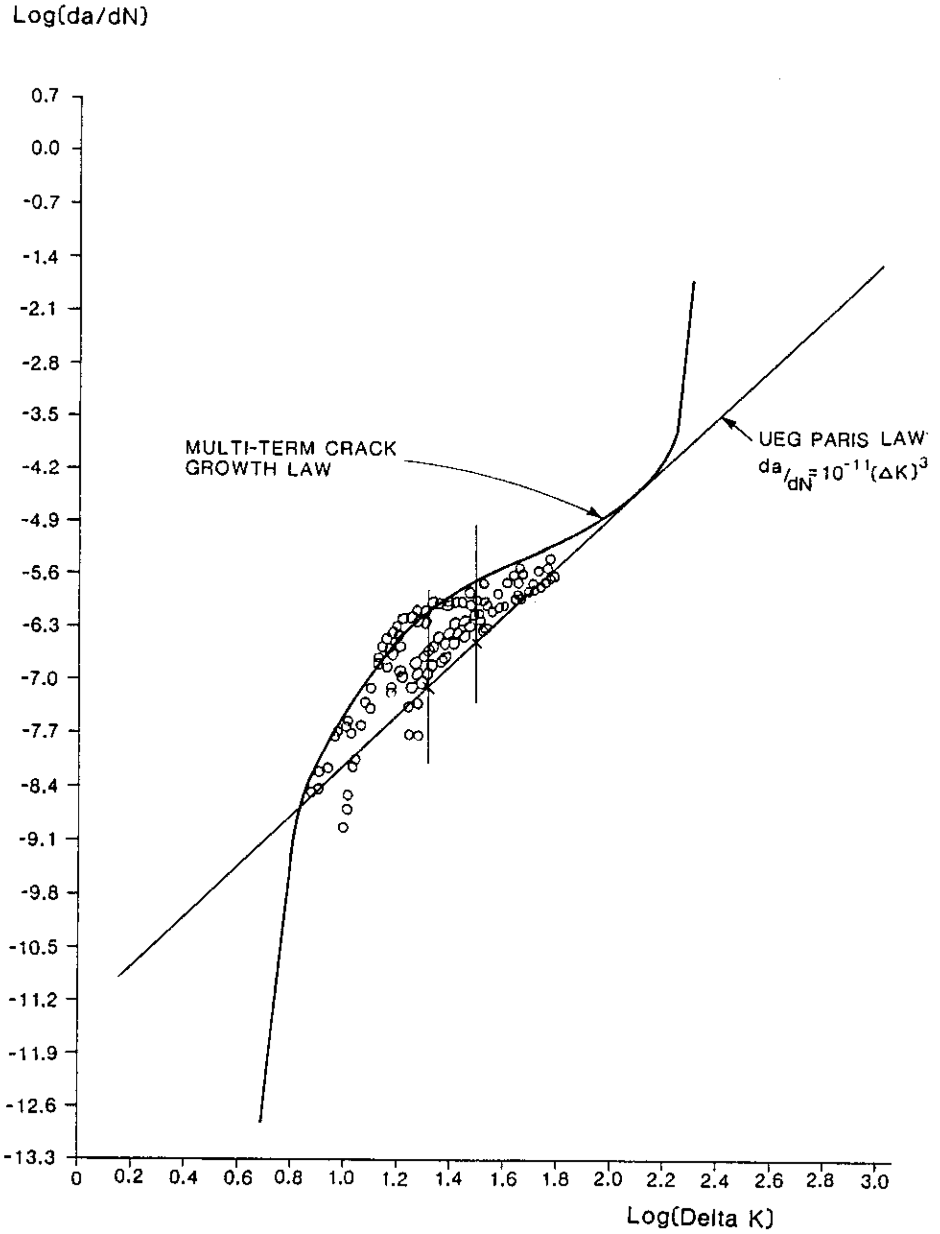


Figure 8.23: *The crack growth law of Equation 11 compared with a Paris law*

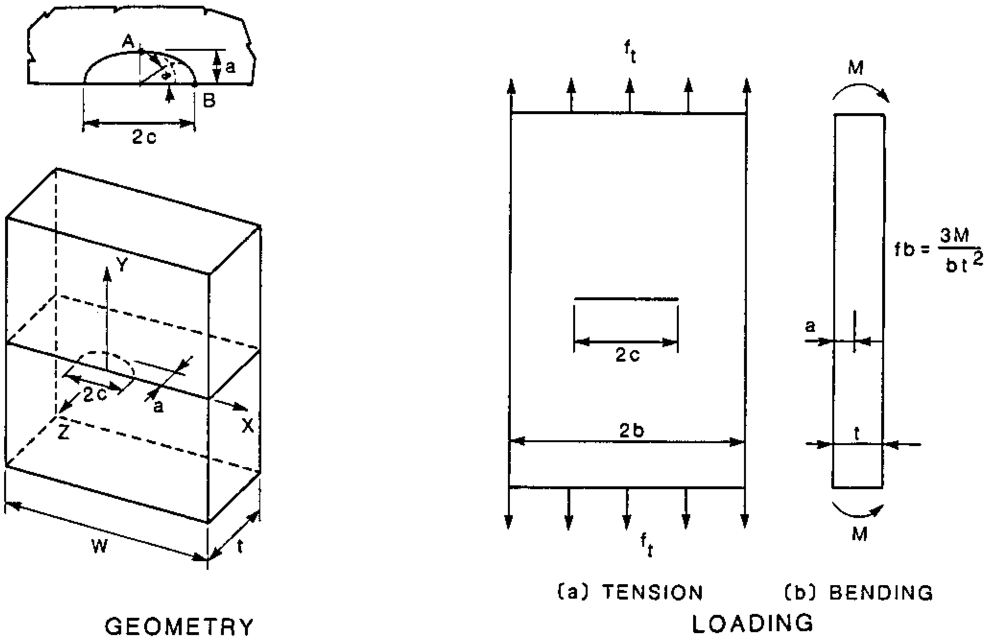


Figure 8.24: *Surface crack in a flat plate*

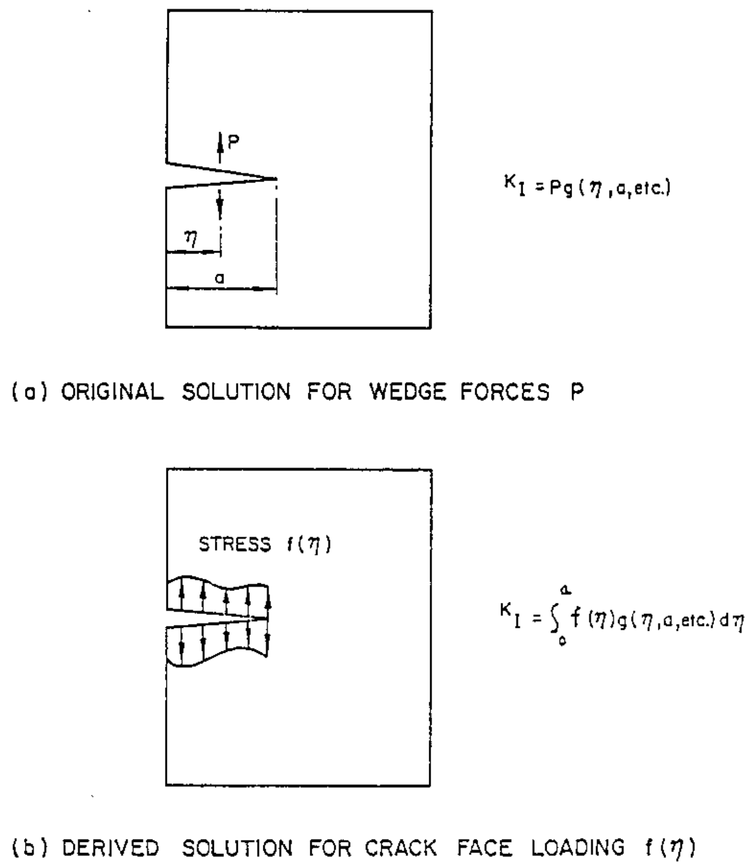


Figure 8.25: *Development of stress intensity solution from the case of wedge opening forces*

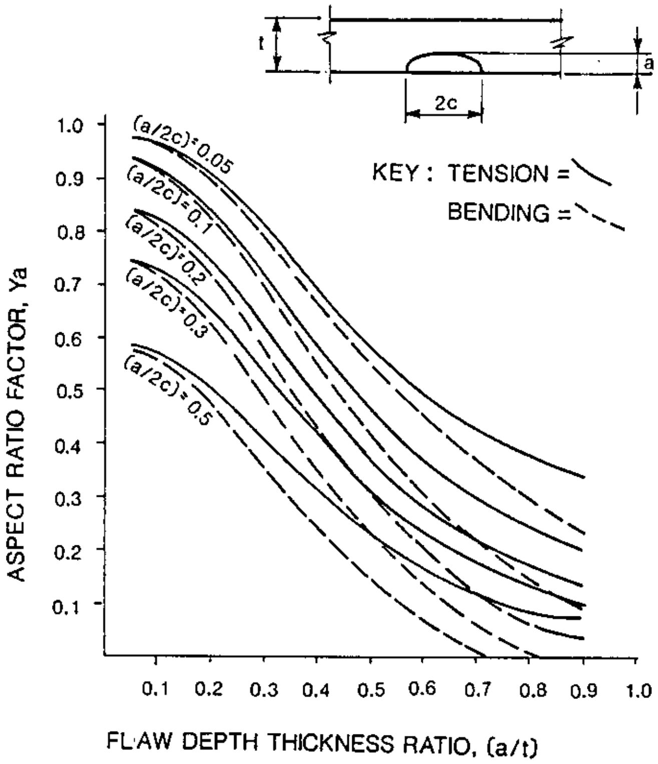


Figure 8.26: *Aspect ratio correction factor, Y_a*

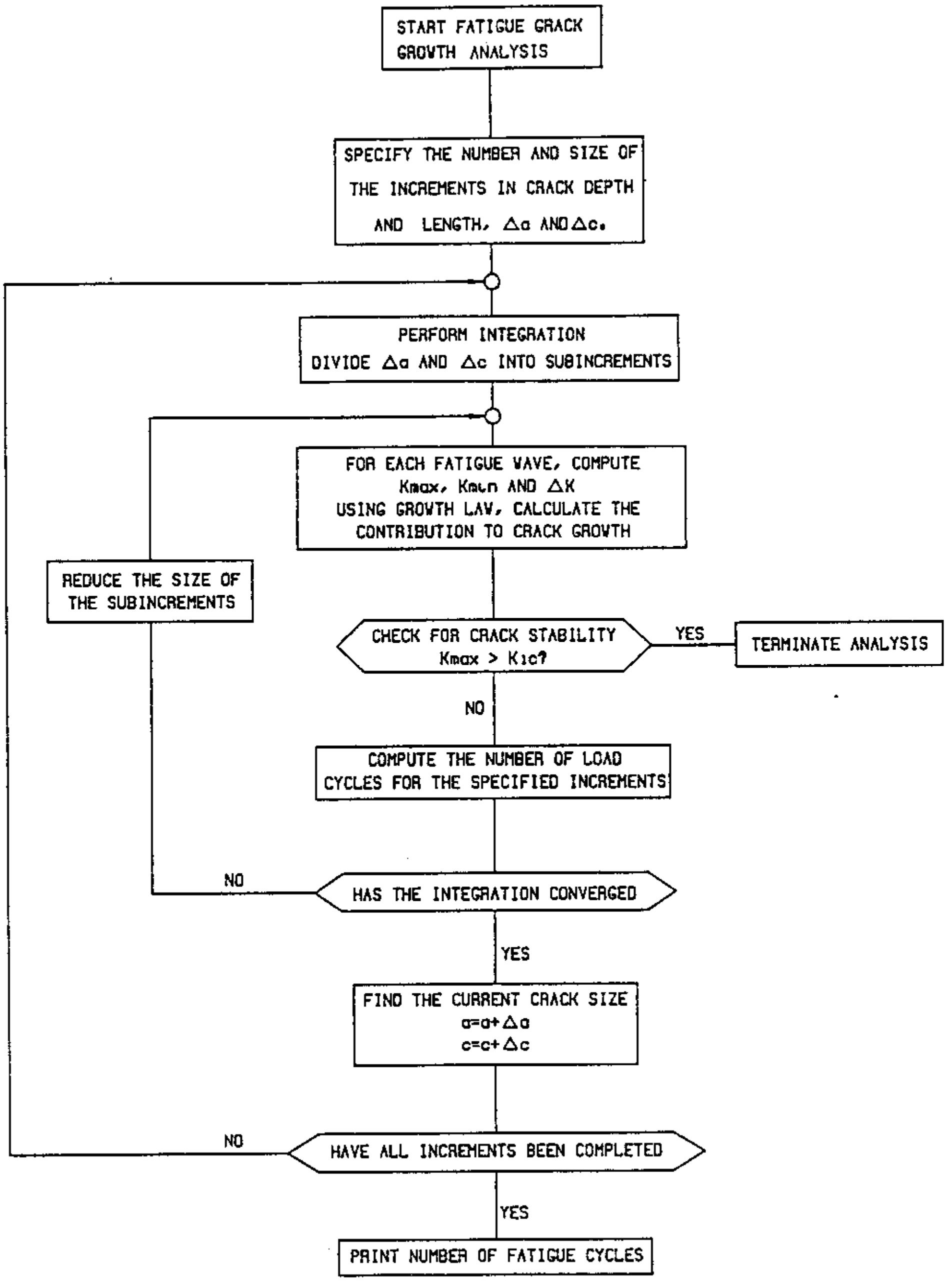


Figure 8.27: *Flowchart for fatigue crack growth computation – part-through cracks*

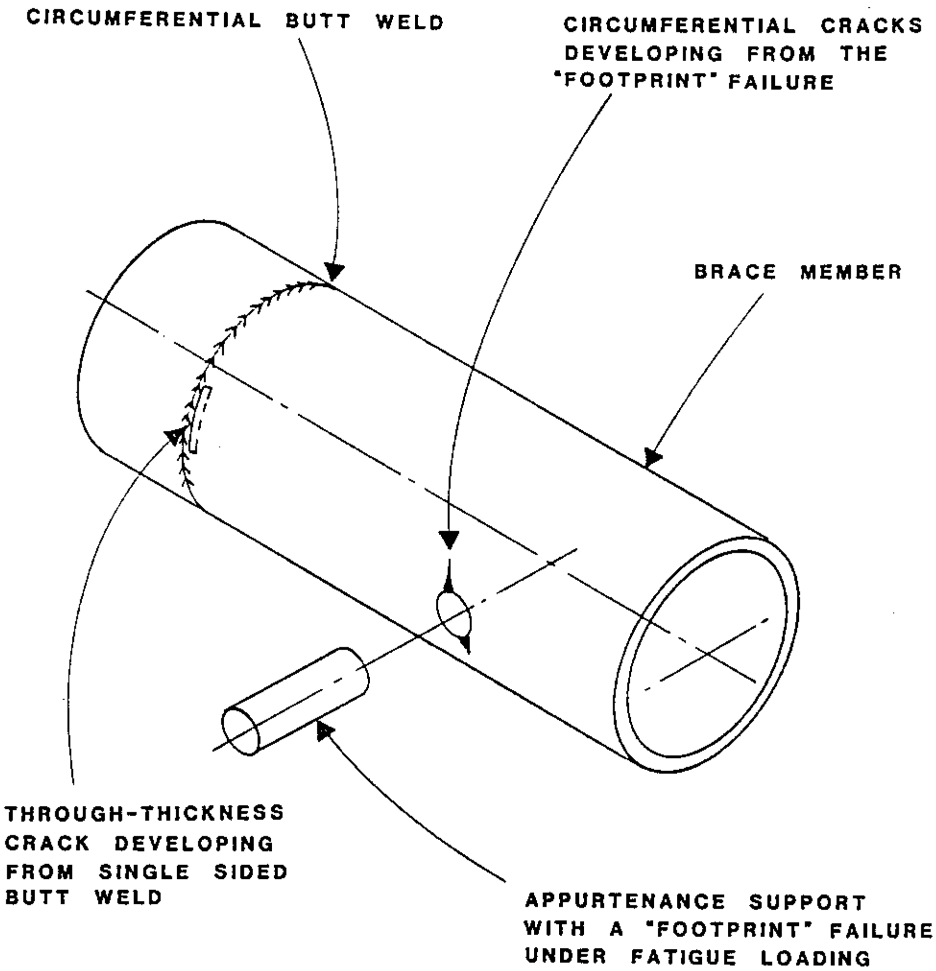


Figure 8.28: *Typical through-thickness crack geometries in a tubular member remote from a joint*

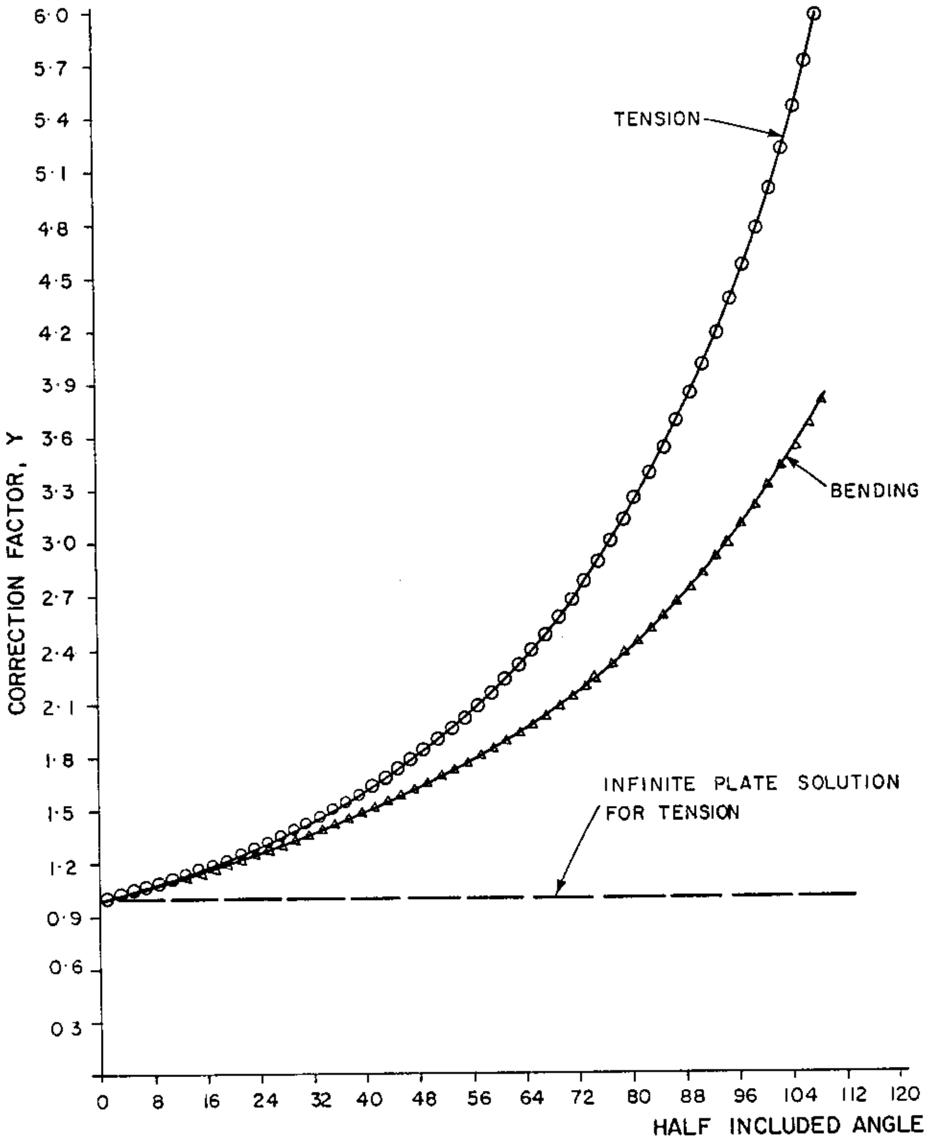


Figure 8.29: *Correction factors, Y_t and Y_b, for use in stress intensity factor solution of Equation 21*

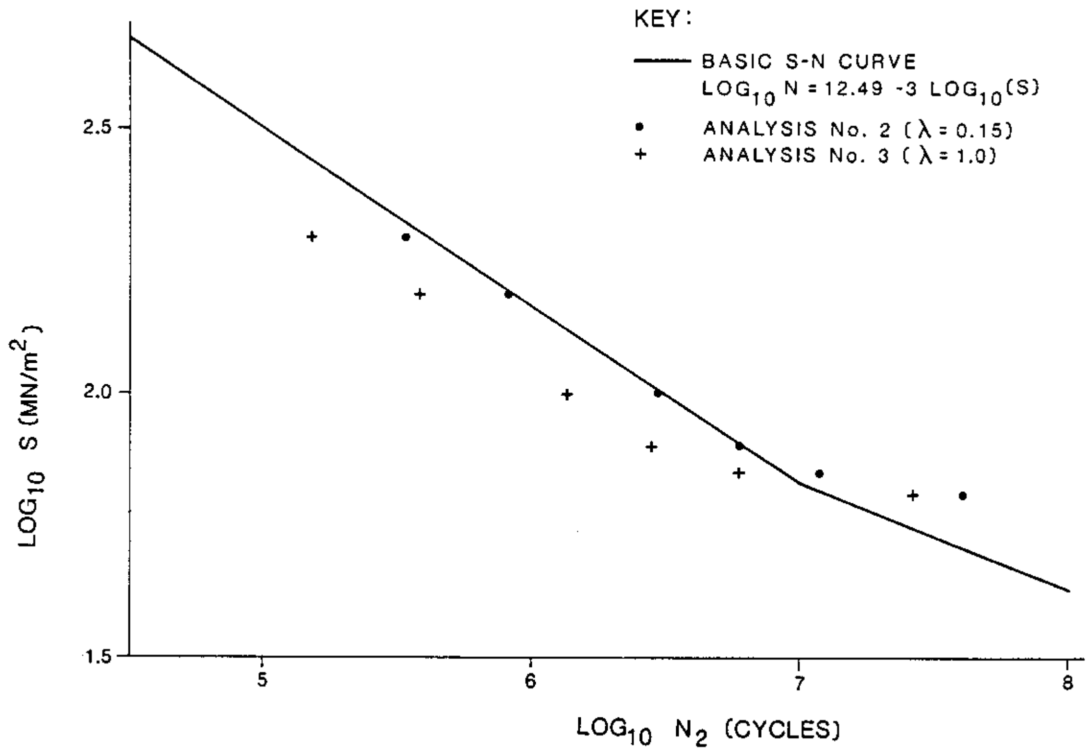


Figure 8.30: *Crack growth model with varying λ compared with experimentally derived S–N curve*

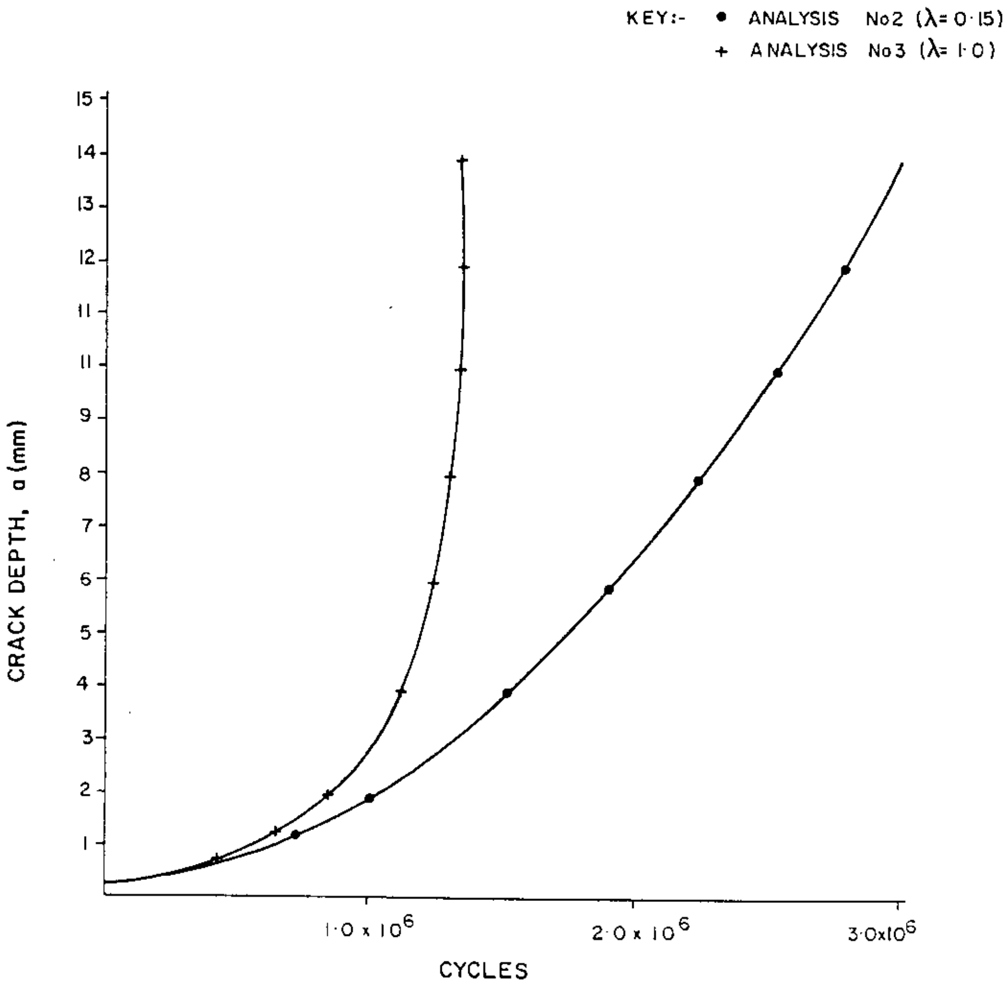


Figure 8.31: *Effect of stress distribution factor, λ, on crack growth characteristics*

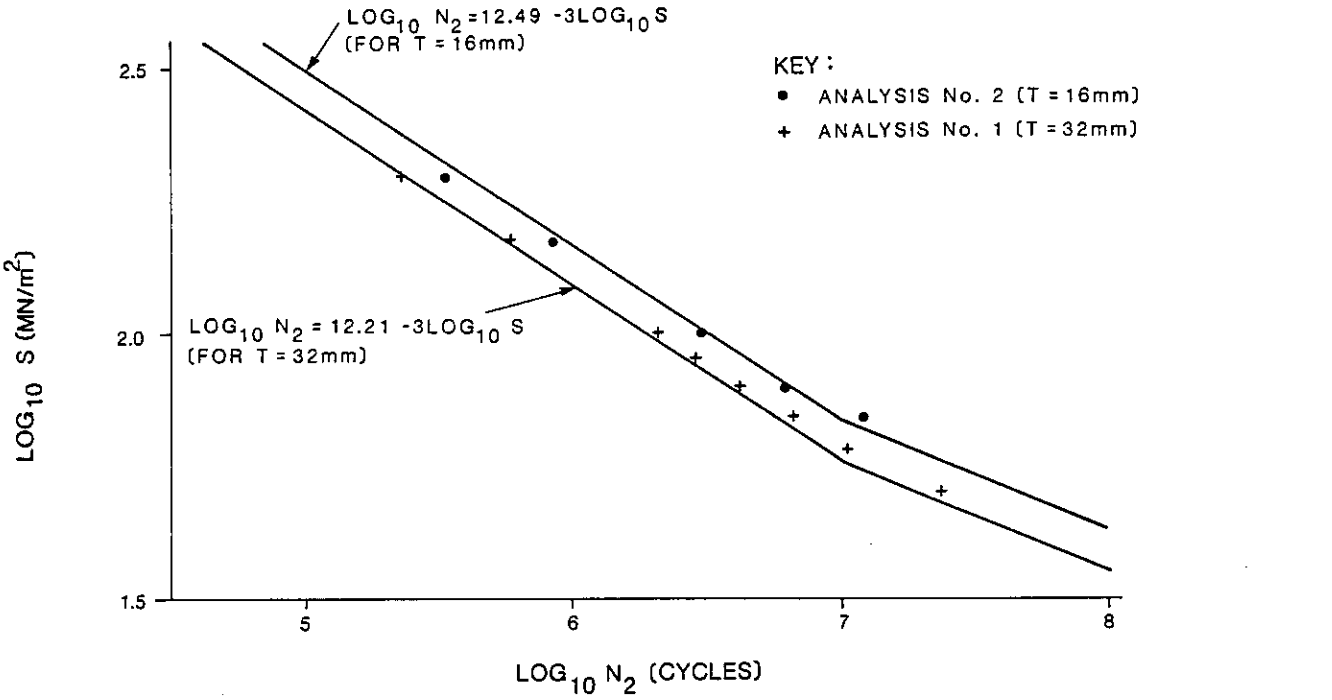


Figure 8.32: *Effect of wall thickness on fatigue life*

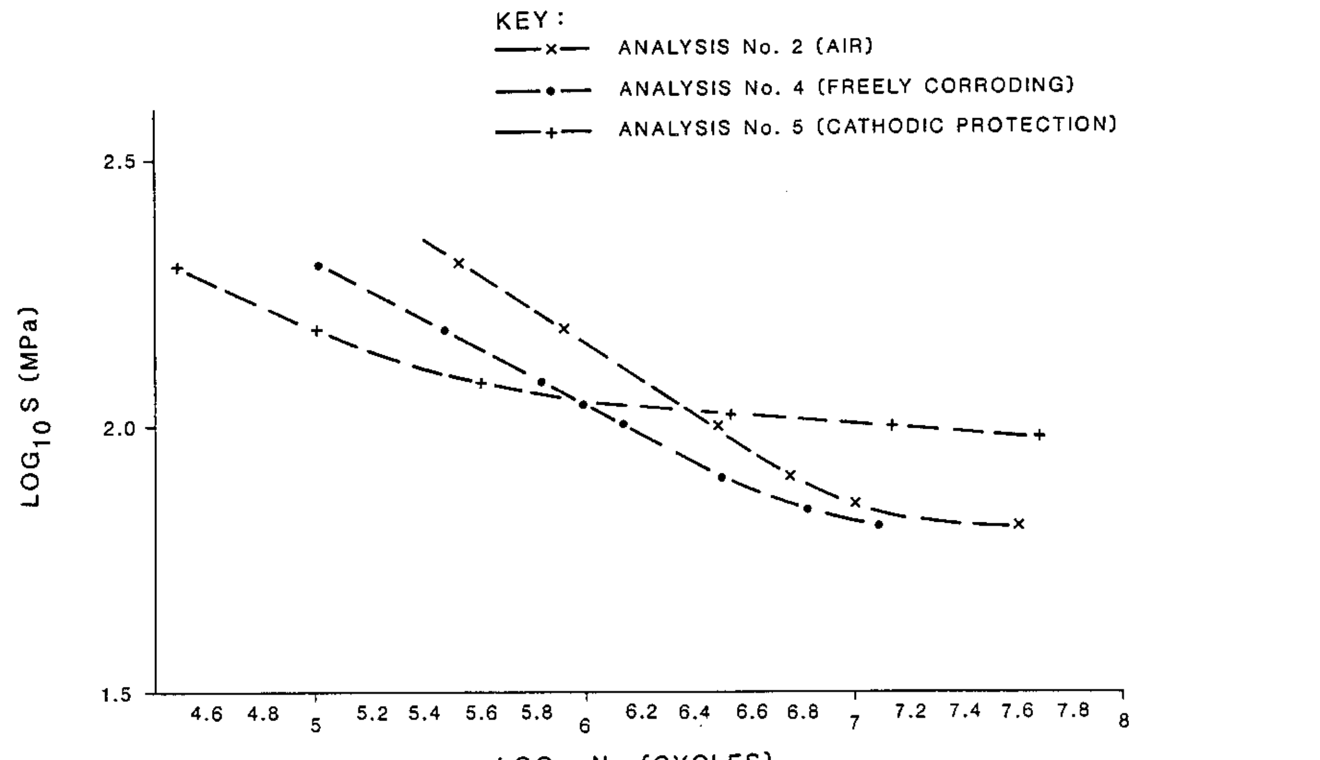


Figure 8.33: *Effect of environment on fatigue life*

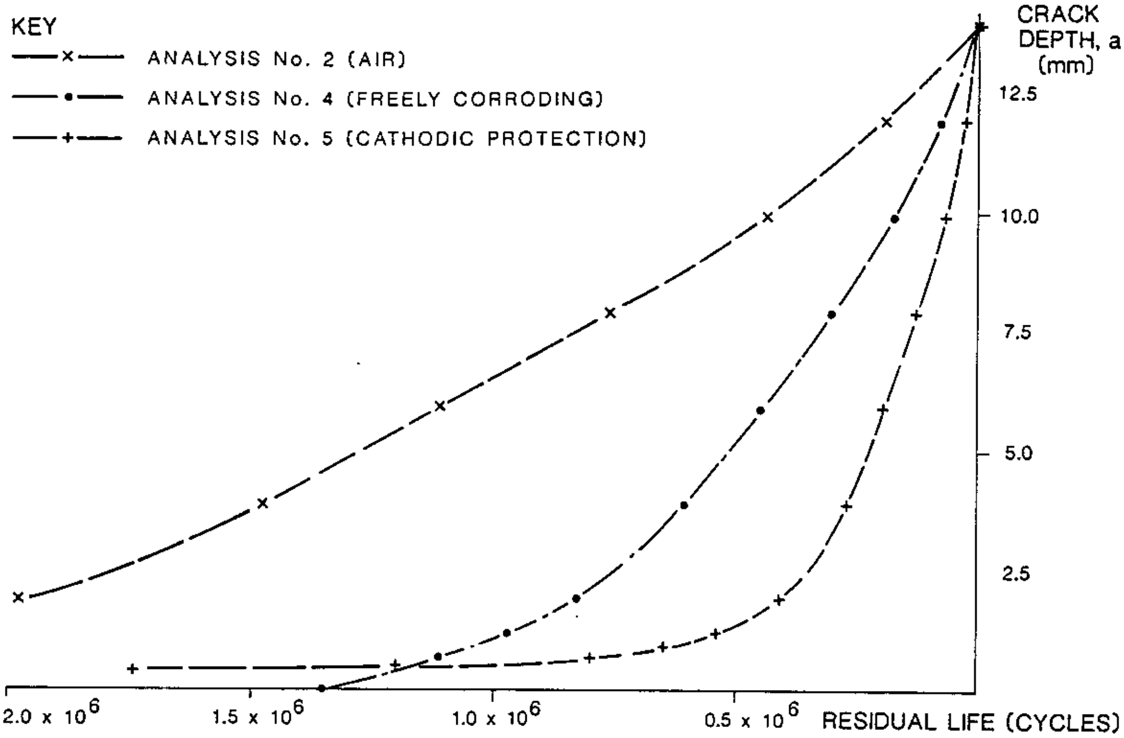
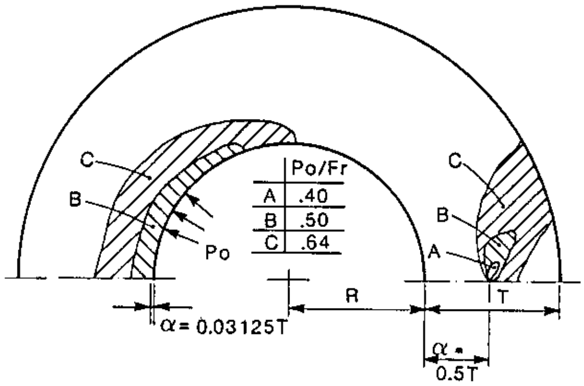
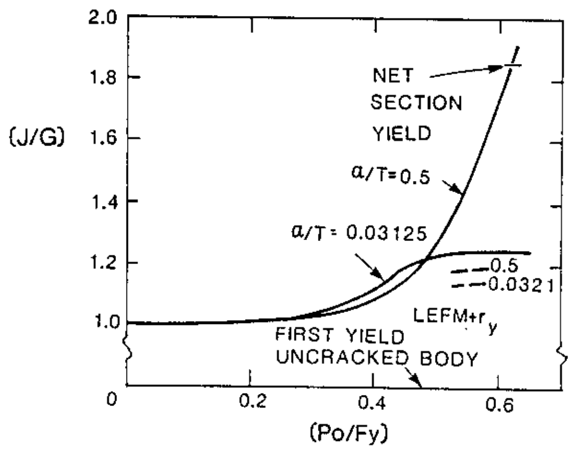


Figure 8.34: *Crack depth versus residual life for three environments*



PRESSURISED CYLINDER WITH INTERNAL CRACKS



CRACK DRIVING FORCE VERSUS LOAD

Figure 8.35: *Effect of plasticity on crack behaviour*
(From Reference 8.37)

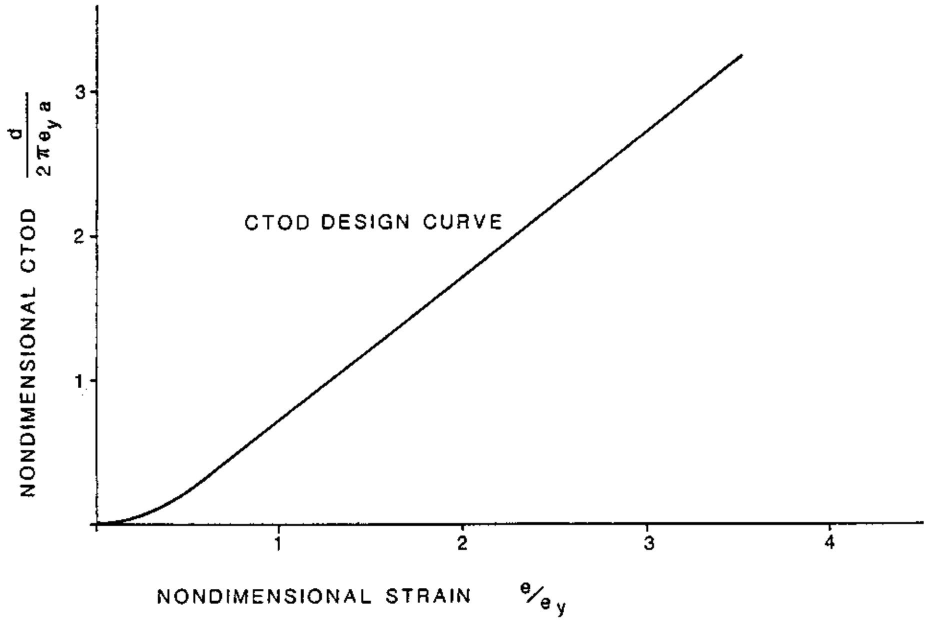


Figure 8.36: *CTOD design curve*
(From Reference 8.41)

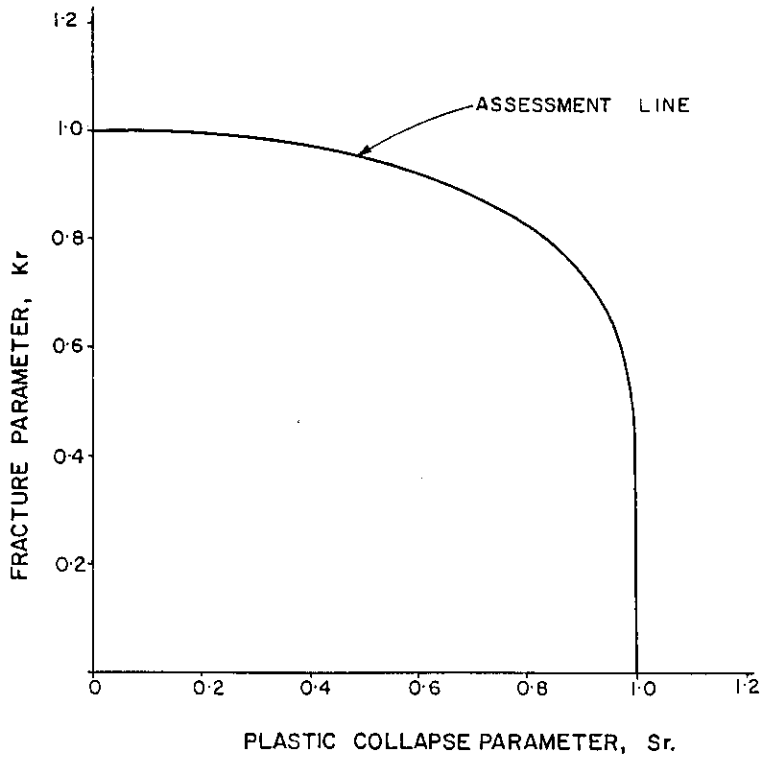


Figure 8.37: *The R6 failure assessment diagram*
(From Reference 8.36)

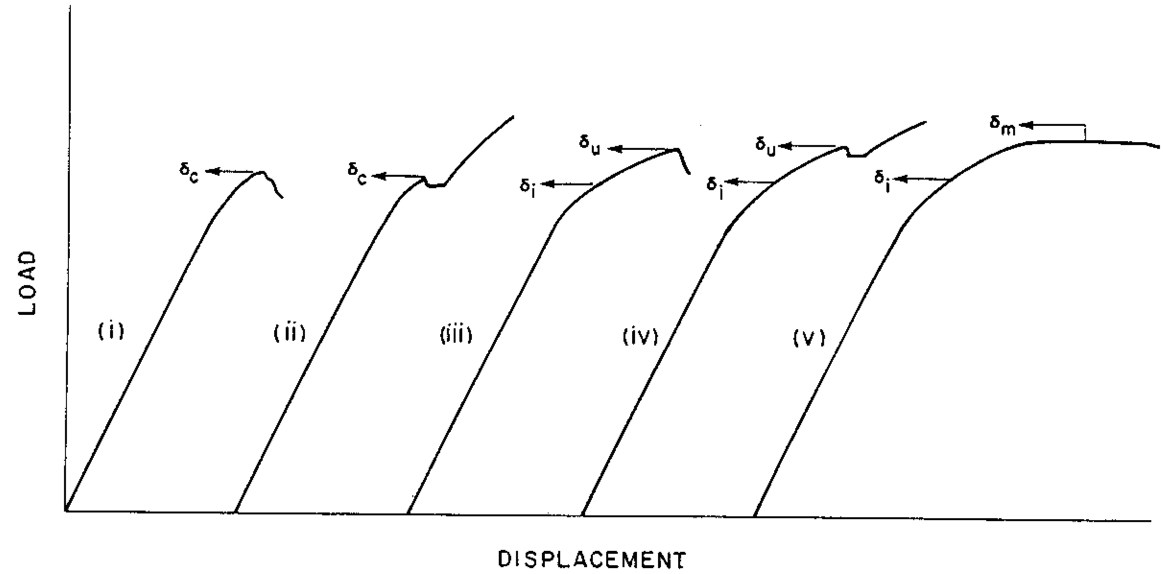
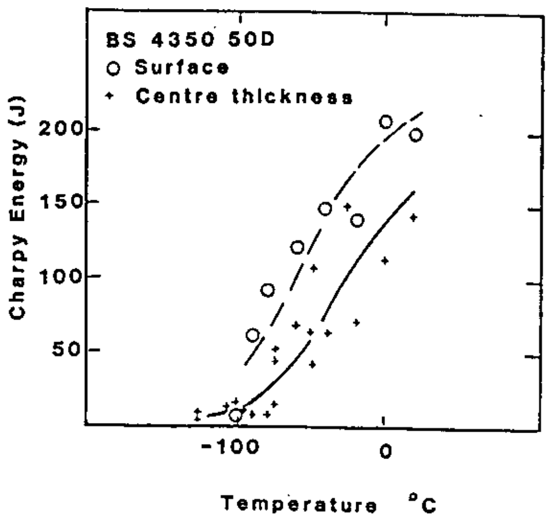


Figure 8.38: *Load-displacement graphs for CTOD showing various types of behaviours*



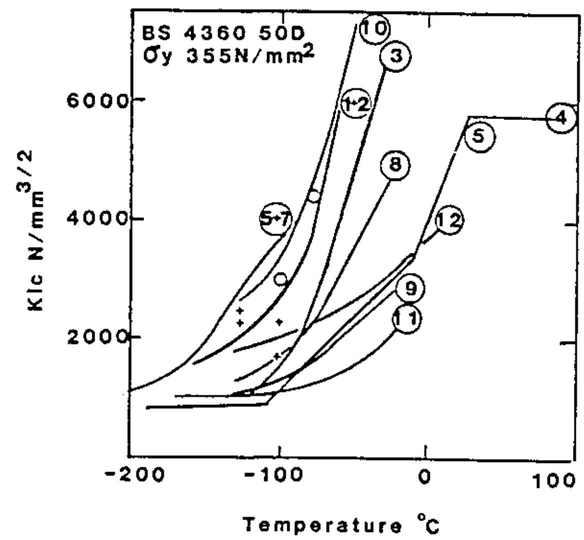


Figure 8.39: *Comparison of predicted K_{IC} curves with experimental K_{IC} values for Grade 50D steel with Charpy transition curve as shown above*
(From Reference 8.53)

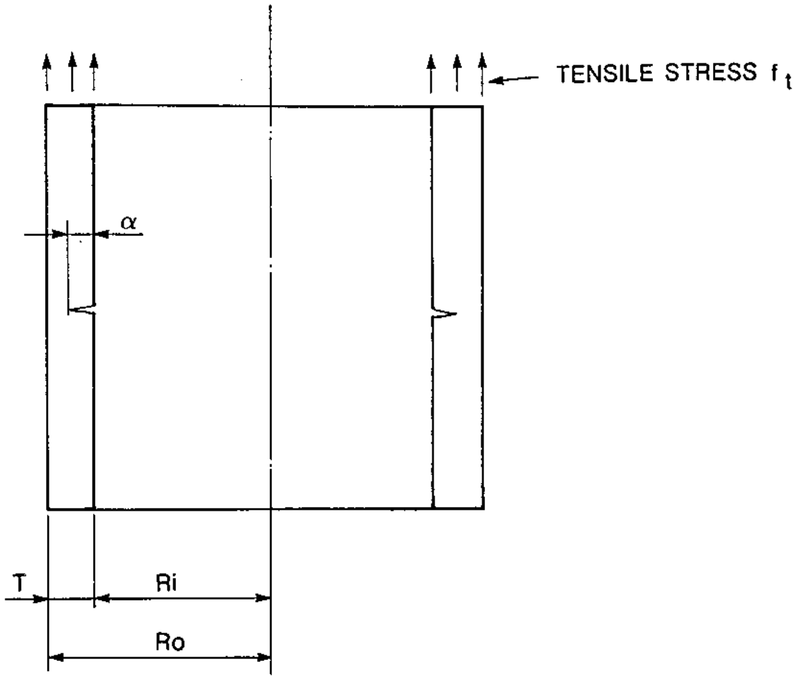


Figure 8.40: *Benchmark studies – internally cracked cylinder under tension*

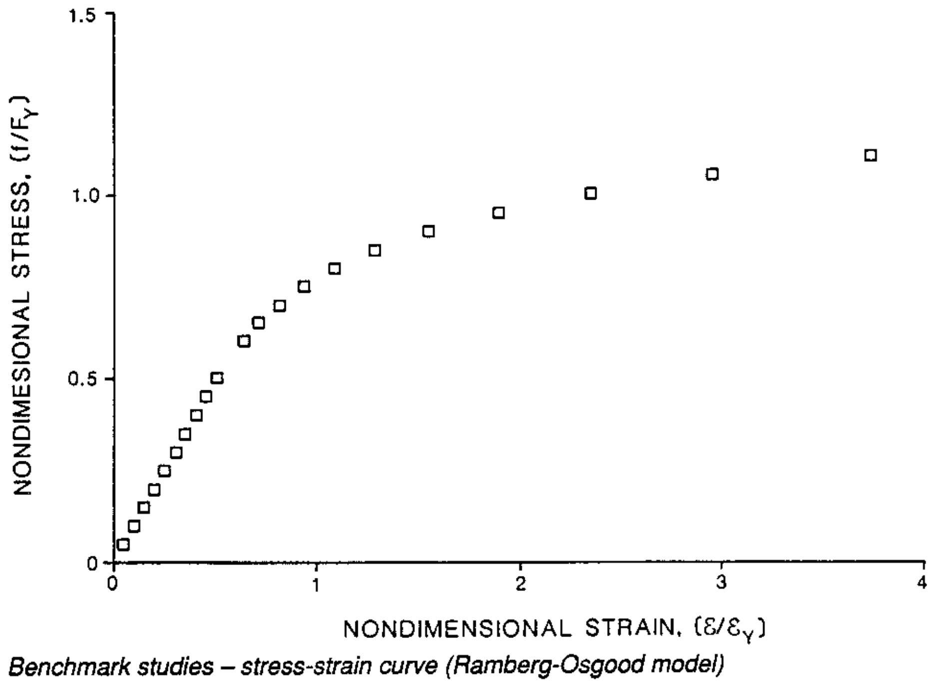


Figure 8.41: *Benchmark studies – stress-strain curve (Ramberg-Osgood model)*

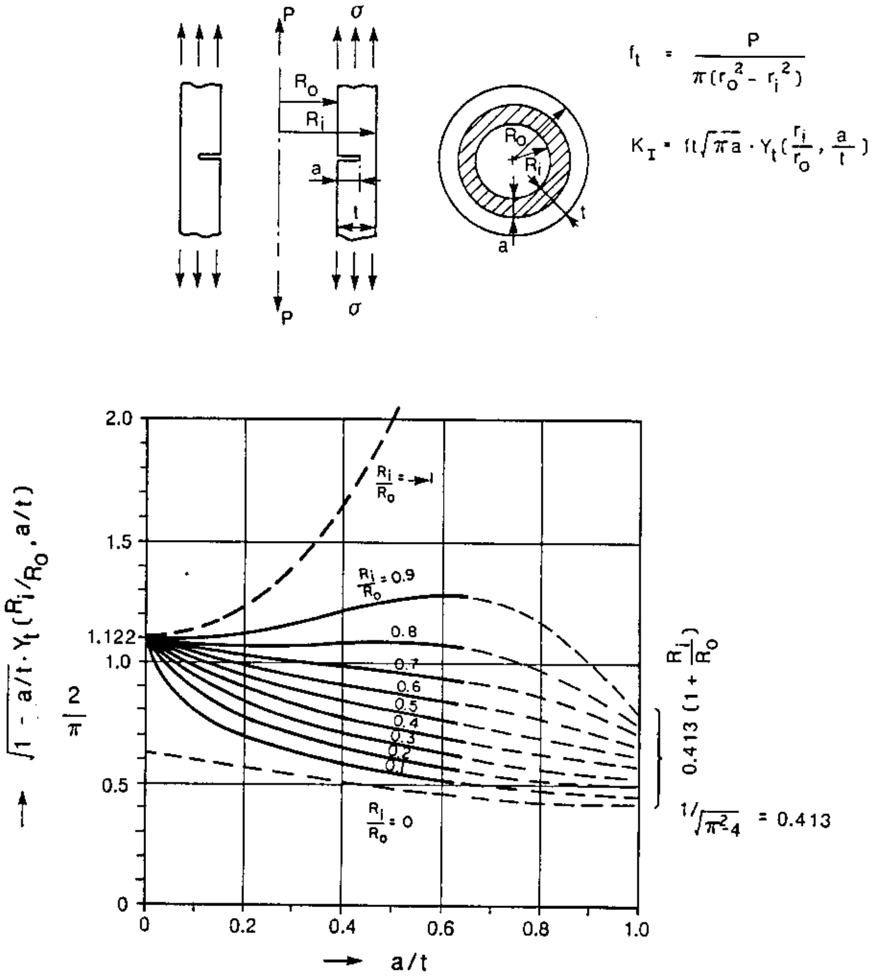


Figure 8.42: *Benchmark studies – stress intensity factor solution*

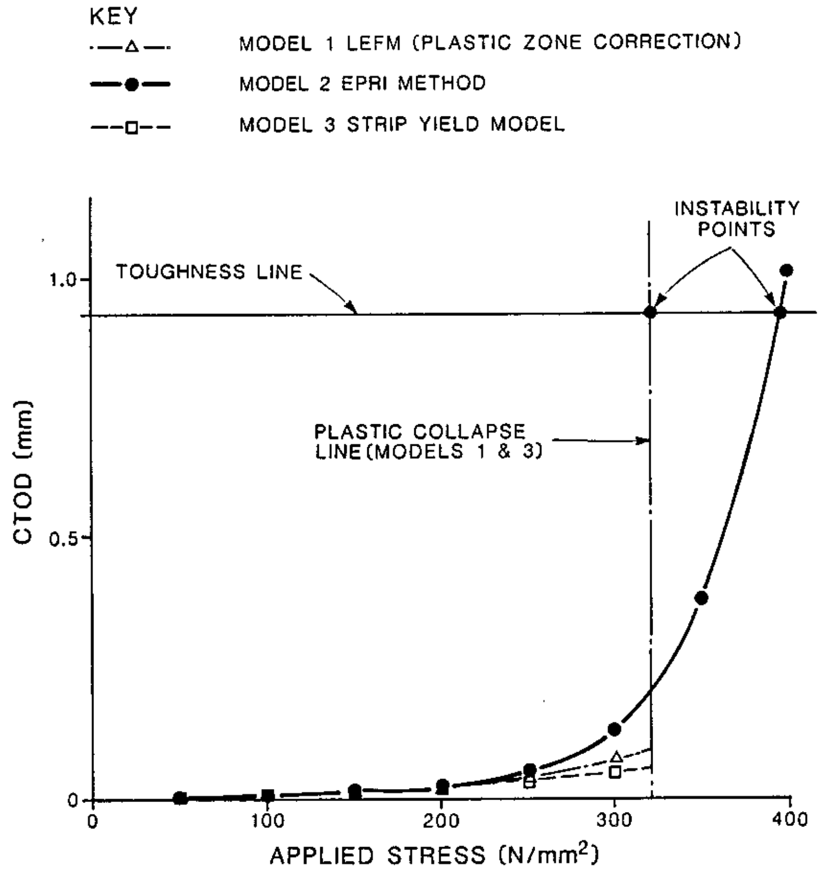


Figure 8.43: *Benchmark studies – stability diagram*

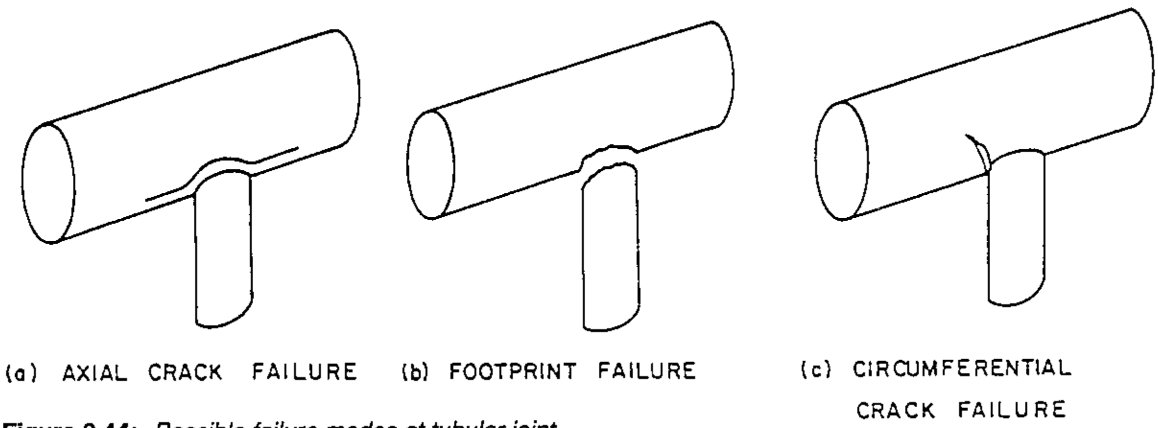


Figure 8.44: *Possible failure modes at tubular joint*

Part C

Interaction between design and inspection

9 Design-inspection interaction

9.1 INTRODUCTION

The designer of a new structure is in a unique position to affect the inspection burden over the lifetime of the installation, and it is proposed that lifetime inspection costs can be optimised by integrating his design approach with the philosophy developed in Chapters 3 and 5. Considerations for the designer and details of the approach he should adopt in ensuring that inspection needs are optimised are discussed in this chapter.

It should be stressed that the recommendations made here should not be implemented in isolation; the in-service inspection considerations, described in detail in Chapter 5, must be considered at the design stage if the capital cost/inspection burden trade-off is to be realised.

The implication of the above is that the inspection philosophy should be incorporated into the design premise for a new installation. In preparing the premise, and interpreting and applying it as design proceeds, it is important that representatives of the operating departments of owners work in conjunction with design development teams.

When design is complete, continuity is needed to ensure that the designed-in inspection philosophy is correctly interpreted and exploited by the operating departments. Collaboration during design should help achieve this aim, but written documentation is also important. This subject is addressed in Section 9.3.

In addition to overall design philosophy, there are many ways in which attention to design detailing can help ease inspection difficulties, leading to reduced cost and increased safety of inspection operations. These are discussed in Chapter 10.

9.2 DESIGN FOR OPTIMUM INSPECTION

Three possible design approaches were discussed in Section 2.8.4 – fail-safe design, design for minimal inspection and the ranking tree approach. It was concluded that emphasis would be placed on the ranking tree approach as this was applicable to both new and existing structures and development of this methodology was the subject of Chapter 5. Nevertheless, there are aspects of the other two approaches which can be adopted when considering the design of new installations and which are compatible with the ranking tree approach. These aspects are utilised in the approach developed below, but within the ranking tree framework developed in Chapter 5.

Section 2.8.2 concluded that it is not possible to design a structure that is 100% reliable, because uncertainties in strength of components and the loading in them can never be known with certainty. Nevertheless, by increasing the degree of conservatism in design (which usually involves an increase in cost), the designer can decrease the uncertainties involved. Thus the designer is faced with a dilemma – where should he set the balance between safety and cost? The problem is illustrated in Figure 9.1.

In practical terms, the designer is faced with a two-stage problem in coping with this dilemma. Firstly, overall performance criteria must be set for each component commensurate with its importance to the integrity of the structure. Secondly, a single design must be selected from the range of possibilities which optimises the trade-off between initial capital expenditure and subsequent in-service inspection expense.

In terms of the component criticality model developed in Chapter 3, performance characteristic setting is related to the 'consequence of failure' dimension, whilst the selection of a specific design to meet the set criteria relates to the 'likelihood of failure' dimension. The designer is in a position to affect both of these factors.

This section considers factors affecting the setting of performance criteria, and Section 9.3 addresses the subsequent financial trade-off in more detail.

As a general rule, designers should concentrate their attention on components whose failure is of high consequence *before* considering the likelihood of the component's failure.

Widespread use of design codes has largely sheltered the designer from having to make judgements about the balance between anticipated loading régimes and required strength characteristics of components. It should be remembered that these codes are largely based on empirical evidence from onshore, not offshore, engineering experience. Where the consequences of component failure are high, and the costs of fabricating the component are also high, a detailed expert review of the controlling criteria is appropriate, particularly if input is available to enable a probabilistic rather than a deterministic appraisal. Such studies may reveal that unnecessarily conservative assumptions have been used.

An alternative route, open to the designers of support structures, is to reduce the criticality of components by increasing structural redundancy. This is akin to a 'fail-safe' approach, in that the structure can be so designed that failure of one or more components redistributes the loading to other members and joints, without immediate global failure. The disadvantage is that structural complexity is usually increased and uncertainty about actual in-service loadpaths increases. However, inspection techniques are more sensitive to complete failure than to minor defects, and this can be used to advantage. For instance, continuous monitoring techniques (see Section 7.1.4), which can be applied globally at relatively small expense, might become a practicable alternative to costly and unreliable local inspection if redundancy is sufficiently increased.

In determining the conceptual design of new structures, the low probability of detection of defects using currently popular techniques is a factor that needs to be borne in mind by the designer. He should always aim to maximise the defect tolerance of critical components. The approach to component ranking in this respect is fully developed in Chapter 5. In this context, 'fracture critical' refers only to the consequence aspect of component failure.

When fracture critical components have been identified, design optimisation should concentrate on:

- identifying the likely type and propagation rate of defects, and their impact on the structure (see Chapter 8)
- ensuring that the rate of propagation of defects is compatible with available inspection techniques (ie, that there is a high probability of identifying the defect before it has reached a critical size – see Chapters 5 and 8)
- identifying design modifications that will ease the inspection burden (through detailing, replacement of MPI with flooded member detection, monitoring, etc)
- introducing alternative loadpaths (redundancy).

9.3 TRADE-OFF BETWEEN CAPITAL AND OPERATING EXPENDITURES

Having set the performance criteria of components on the basis of safety/structural integrity ('consequence of failure' criteria), the designer may be faced with several options for the detail design of the component. For instance, by reducing the thickness of material, static strength requirements for a component may still be met adequately but fatigue life reduced, leading to heavier in-service inspection requirements.

Evidence now exists to demonstrate that the expectation of identifying a small defect in a component is low (see Section 2.6). This has two implications on design:

- more attention must be paid to making fracture-critical components fracture proof (ie in need of no onerous inspection throughout their lifetime), to reduce the number of components requiring inspection over the lifespan of the installation
- attention should be paid to increasing the critical defect size (ie the size preceding component failure) to increase probability of detection during inspection.

These expedients will help reduce inspection time at each site and reduce the number of sites at which inspection is necessary. Unfortunately, it must be recognised that the inadequacies of current techniques and the probabilistic arguments demonstrated in Figure 2.1 imply that the *frequency* of inspection at the critical sites must increase, which offsets the first benefit.

In practice, total available inspection time per season is likely still to be the controlling constraint on the inspection team. Consequently, to ensure that the inspection team is able to maximise attention to critical components, the designer should aim at 'design for minimal inspection' for all components (see Section 2.8.4).

There will be some instances where the cost of designing more conservatively to meet this aim will rise dramatically for marginal safety benefit. This will be particularly true of major components in redundant structures and all parts of non-redundant structures.

In these instances, the trade-off between initial capital expenditure and the increased inspection burden implied by a lighter design must be investigated. Careful engineering studies should be undertaken to determine the likely lifetime costs of inspection at today's prices. Inputs into the cost determination will include:

- likelihood and consequence of failure (see Chapter 5)
- expected frequency of inspection
- cost of inspection (itself a function of considerations such as depth, location, difficulty of identifying a defect of critical size, technique to be used, etc).

If there is any material risk that failure could nevertheless occur, then the consequential costs must also be considered. The cost of lost production must be included in the equation if a component failure requires temporary or extended production shutdown.

Having identified the costs of inspection against the cost of heavier design for a given level of safety risk (as determined by the criteria discussed in Section 9.2 above), the alternatives must be evaluated using discounted cash flow methods. The appropriate discount rate is the owner's (real) cost of capital for the project. If there is uncertainty about the accuracy of the anticipated costs of inspection and any consequential losses, these should be accounted for by weighting the outcomes of several scenarios rather than adjusting the discount rate.

In summary, the approach should be:

- to design to avoid inspection unless the costs appear prohibitive – this ensures against overburdening the scarce offshore inspection resources (particularly access time) in future years
- use discounted cash flow methods to evaluate the capital versus operating expenditure trade-off taking due account of possible consequential losses.

9.4 HANDOVER FROM DESIGNER TO OPERATOR

To achieve maximum benefit from designing for optimum inspection, it is essential to achieve effective handover at all stages from conceptual design development through to final handover to the offshore operating teams. It was suggested in Section 9.1 that continuity could be achieved both through personnel and through documentation; in practice, the timescales and the range of skills involved at each stage of development make it unlikely that the same individuals will see the project through from concept to completion. Consequently, a considerable burden must fall on formalising procedures and documentation.

One feature of the rational approach to inspection planning detailed in Chapter 5 is a 'review panel' of experts from various disciplines to advise on aspects that either would not be cost effective or have insufficient data available to allow wholly objective analysis. If possible, this team should be formed at the time that the preliminary design premise is being established by the owner, and one of its first jobs should be to discuss and formulate the inspection-related inputs into the premise. Formal guidelines will assist continuity as personnel on the team change through time.

For ease of use and update of the component weighting model described in Chapter 5, it was suggested that a microcomputer be used to help develop and to store the relevant inspection data for each component. For new structures, the computer model should be built up during the design phase and used to help designers and owner's representatives on the development team identify critical components on which special attention is merited. It is intended that techniques analogous to those described in Chapter 5 (eg postulating defects and gaining understanding of the behaviour of the structure as a consequence) will be used for ranking components, but that, rather than leave the critical components as 'high ranking', attempts will be made to reduce their criticality by design refinement.

As the project progresses from design to fabrication to installation to eventual service offshore, relevant documentation will be built up relating to each component. This will include materials certificates, welding procedures, NDT reports, design modifications, etc. As far as possible, any material effect on the likely service performance of the component (built-in defects, suspect materials, etc) should be identified, and its ranking changed accordingly.

It is apparent from the above that the preparation and maintenance of the component weighting model can be integrated with a more general database on the components, one which incorporates all the detailed documentation pertaining to each component. In addition to the documentation mentioned above, criteria used by the review panel in establishing the ranking of a component should also be stored in the database, together with any relevant notes on arbitrary decisions taken in arriving at those criteria.

It will also be apparent that unless this (sizeable) task is specifically delegated to a team who are largely independent of day-to-day progress chasing, it will not get done! Different operators will take different positions on the usefulness or otherwise of an integrated database and will allocate resources accordingly, but it is proposed that the functions described belong in the domain of Quality Assurance and that this would be the most suitable group to undertake the upkeep of the model.

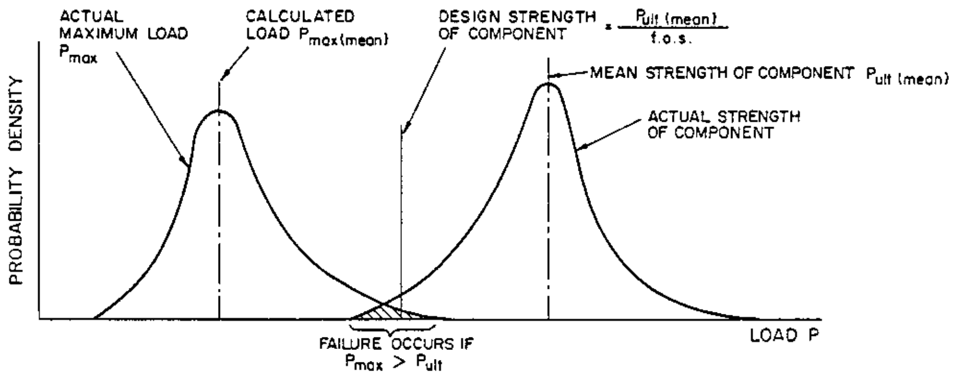


Figure 9.1: *Relationship between component strength and applied load*

Conservatism in design can be increased by:

	Effect	*Possible mechanism*
1.	decrease the loading	increase redundancy
2.	decrease standard deviation of loading	decrease redundancy
3.	increase the component strength	thicker material
4.	decrease the SD of component strength	better quality material

In view of the conflicting requirements/effects of 1 and 2, action to increase confidence in the strength of the components is the most practicable means of introducing conservatism. Increased cost is incurred.

10 Design for ease of inspection and monitoring

10.1 INTRODUCTION

With the benefit of hindsight it is obvious that many of the practical problems frequently encountered during underwater inspections could have been avoided or reduced by actions at the design stage. In many cases, dramatic improvement could have been effected at little or no extra cost.

This chapter examines the most persistent problems and considers their solutions but does not provide definitive design guidelines. Structural forms, operating conditions and company practices vary too much for that to be possible. It should also be appreciated that the lists are not exhaustive and other problems may be encountered, particularly with the newer types of structures being developed and for inspection techniques currently under development. As a routine, therefore, it is recommended that diving and inspection specialists be consulted throughout the design process, with a view to identifying and avoiding potential difficulties.

It is hoped that the ideas presented here will promote a greater awareness amongst designers of the problems facing diver/inspectors, but the degree to which this awareness is reflected in future designs is dependent on the attitudes of operators. An attitude which discourages capital spending is not entirely consistent with the design of more easily inspected structures. Although many of the practices described here to rationalise and streamline inspection will not affect design costs and timescales significantly, optimising the structure for minimum inspection could be relatively expensive and time consuming at the design stage.

The design cycle for offshore structural installations is generally a progression – from feasibility, through concept, detail design and fabrication to installation. These stages of the cycle are considered below but the adoption of a specific range of techniques for inspection is not presupposed; each operatior will have preferences and will have incorporated varying levels of remote monitoring into his inspection design premise. Nevertheless, it has been emphasised that the structure can never be designed to give 100% reliability in all circumstances. Thus it is appropriate to introduce features into the design to allow easy access to as much of the installation as possible, to allow:

- random inspections, as recommended at the end of Section 5.3.3
- (unexpected) repairs.

Most of the detail of this chapter refers to inspection by divers; it may not be entirely relevant should an alternative means of intervention or inspection be adopted.

Table 10.1 summarises the detail points made in Sections 10.2 to 10.5.

10.2 CONCEPTUAL ENGINEERING

The structural configuration, including the basic sizing of members, is set during the conceptual design phase. For most developments, this phase is a relatively simple process, based on experience and usually completed in a short timescale. The fundamentals of an inspection strategy must therefore be adopted very early in the design process if the strategy is to be considered effectively at this stage.

A prerequisite of conceptual engineering is the design specification which details the operational requirements of the structure. Inspection influences a number of these criteria and some broad inspection philosophy has to be established before the specification can be produced. The inspection philosophy affects the following:

- target design fatigue life
- level of redundancy (not currently a normal requirement for steel platforms but pipelines and sub-sea installations do consider redundancy as part of the basic criteria)
- level of permissible damage
- onboard diving system requirements
- requirements for pipeline pigging
- replaceable items
- marine growth profiles.

Alternative strategies can be considered during the conceptual design phase. In particular, the relative costs of providing higher redundancy or lower fatigue lives – or both – can be evaluated.

At the end of this phase, the overall configuration of the structure will have been defined, and with it the level of redundancy and the general level of target fatigue lives. Boat impact will have been considered (usually in terms of providing redundancy in the upper bracing). It is suggested that the scope of redundancy studies be extended to include all the primary structure and that criteria for the fatigue assessment should take account of inspection requirements.

A number of factors which influence the ease of inspecting the installed structure are also defined very early in the design process, including:

- brace intersection angles at tubular joints
- positions of risers, caissons and other appurtenances
- position of the inspection intervention system
- access to replaceable items (such as riser valves and connections on fixed platforms, or tethers on tension leg platforms).

Sections 10.2.1 and 10.2.2 here give more detail of some of the items in the above lists.

Before proceeding to the detail design, it is recommended that the results of the conceptual design phase are reviewed by the operator's production and inspection specialists.

10.2.1 Tubular joints

Access to tubular joints for inspection is usually improved if the number of members meeting at each node is kept to a minimum.

Consideration should be given to adopting the simplest joint layout even if there is a penalty of extra weight. Overlapping joints are undesirable from an access standpoint.

The presence of pile guides close to tubular joints may restrict diver access to the joint welds. The guides should be located away from the joints, or the possibility should be considered of using vertical piles in conjunction with underwater piling hammers.

Cleaning and inspecting the 'heel' area on brace-to-can welds has proved difficult, particularly for intersection angles less than 45 degrees. On many existing designs, as much as 20% of the weld length of tubular connections may be uninspectable for this reason.

Whilst intersection angles are likely to be dependent on the structure framing configuration (especially at major joints) it may be possible to increase the angles at some critical joints. Adoption of a more 'open' configuration at the conceptual design stage with wider brace intersection angles would lead to obvious benefits during later inspection programmes. Experience has shown that it is very often the plan bracing level and the conductor framing that are susceptible to this problem.

As an alternative strategy, joints with low intersection angles could be classified as uninspectable and designed accordingly. The viability of this approach depends very much on the certifying authorities and their attitude towards design criteria of items classified as uninspectable.

10.2.2 Effect of the inspection intervention system

In deciding the structural layout of an offshore installation, a primary consideration should be the type of intervention to be used in the underwater inspection programme. It may be the intention to install a diving deployment system (DDS) on the structure or to deploy divers from an independent diving support vessel (DSV). It may be planned that the bulk of the inspection effort will be carried out by remotely operated vehicles (ROVs). Details of these deployment systems are given in Section 7.4.

If it is intended to carry out platform-deployed air diving or ROV operations, dedicated areas should be considered to enable skid-mounted units to be accommodated. If inspection is to be carried out from a DSV, adequate platform mooring points must be provided.

Access for inspection

A deck-mounted DDS consisting of a diving bell running on guide wires or rails requires a clear vertical opening through the structure. The accessible area is governed by the allowable length of the diver's umbilical.

The DDS should be located so that all structural parts requiring inspection lie within the accessible area. Multiple lowering points may be necessary to ensure full coverage of the structure. Figures 10.1 and 10.2 illustrate this access.

If inspection is to be carried out from a DSV, access to the central area of the installation may be restricted by the length of the diver's umbilical. In these circumstances, inspectable items should be as close to the structure perimeter as possible, although other design factors or operational constraints often make this impracticable (eg for risers or outfalls whose position is dictated by topside layout). Consideration should also be given to ensuring higher design fatigue lives for welded joints in the central area of the structure, to reduce their inspection requirement.

The air diving limit

There is a widespread misconception that inspectable items should whenever possible be confined to the air diving range (50 m in UK waters) because air diving operations are generally less costly than mixed gas diving. The problem is that the tendency by many operators to rely on large DSVs as the basis of inspection diving has complicated the economics. If a DSV and mixed gas diving must be employed for the main inspection programme, the occasional use of air divers in the air diving range may be uneconomic. In these circumstances, inspectable items should be avoided at air diving depths as far as is practicable and air diving only used at first framing level. In some cases, with a combined DSV (air and mixed gas), air diving can be undertaken at the same time as saturation diving and the cost penalty of air diving in this situation would not be as great.

Clearly, the decision on the type of intervention system to be used should be made at an early stage in the overall design process. Different diving and access methods are discussed in Section 7.4.

The splash zone

Whatever access system is used, inspection operations are especially hazardous and weather dependent in the splash zone. Inspectable items should be kept to a minimum at this level (in fact structural welded joints tend to be avoided in the splash zone because of the possibility of wave slam on connecting members).

Internal access

Since much of the inspection of floating units is carried out from the inside, man-access must be available to the areas requiring inspection and must not be obstructed by internal stiffeners, diaphragms, etc.

Designing on the basis that fixed structures will be inspected internally is not considered to be a serious proposition; even if a structure could be designed with man-access to tubular joints, safety implications would probably prevent the use of internal inspection.

Topsides layout

The type of diving system used has a considerable impact on the topsides layout of a platform. It affects the size and weight of deployment modules as well as requirements for through-deck access, craneage and lay-down areas. If the intention is to carry out diving operations from a DSV, the location of overhanging platform decks, bridges, flare booms, etc must not prevent the DSV from taking up its position above the diving area.

Pipeline inspection using pigs presents the designer with a number of layout problems, particularly in the deck area. Pigging operations require launching and receiving traps and facilities for handling and storing equipment. The dimensions of typical pig launch and receive traps are shown in Figure 10.3. Pig launching and receiving are potentially hazardous operations and the location of the necessary equipment relative to other platform activities should be chosen accordingly. The minimum negotiable radius of the current generation of intelligent pigs is 3 x pipe diameter[10.1], and this may impose further limitations on the position of plant.

10.3 DETAIL DESIGN

Detail design leads to the production of 'approved for construction' (AFC) drawings and is generally a development of the conceptual design to define all member sizes, joint details, etc as well as the fabrication and installation procedures, etc. The design evolves during this phase, and a multitude of decisions determines the final details on the construction drawings.

In order that ease of inspection is adopted as one of the design criteria in the detail design phase, engineers need to be educated as to its importance. Ease of fabrication is already considered – designers are aware of the relative merits of various fabrication options and know the requirements for welder access, rolling, post-weld heat treatment, erection sequencing, etc. A great deal of this expertise has been fed back from fabrication sites, either brought in by designers' or operators' engineers with site experience or by the employment of fabrication engineers. Similarly, in order to improve the inspectability of offshore structures in service, engineers with operational/inspection experience need to be involved in design. Most of this expertise currently resides with the operators, who have usually retained the responsibility for underwater inspection.

Experience has shown that more engineering effort should generally be put into the design of fenders, boat landings, riser protection, escape ladders and gangways on the lower deck to avoid costly repair and maintenance. For example, bolted connections should not be used at these locations in the splash zone.

Decisions made at the detail design stage affect diver safety and ease of access during inspection, the application of structural monitoring and the defect tolerance of the structure. These considerations are discussed further in Sections 10.3.1 to 10.3.4 below.

10.3.1 Diving considerations and safety

Although better access for diver/inspectors and safer working conditions may not directly improve the fundamental accuracy of underwater inspection techniques, it can be expected that they will improve the reliability and repeatability of inspection results.

Discharges

Discharges from an installation are a significant hazard to divers, particularly when the discharge is toxic or aerated. If discharges cannot be located away from areas of likely diver activity, dual outlets should be considered with a switching facility so that discharge operations can avoid any diver activity. One North Sea operator has retrofitted such a system.

Discharged drill cuttings rapidly build up on lower bracing members and joints. They must be cleared prior to inspection in these areas but this is a hazardous operation as the drilling mud is toxic. A layout where the cuttings are discharged outside the structure and on the down-current side would lessen this problem.

Intakes, covers and grids

Submerged intakes are also a danger to divers. All intakes should be fitted with catch grids similar to the example shown in Figure 10.4, unless they are located clear of diver access.

Grids and covers should not be fitted indiscriminately. Where an item that will have to be inspected offers no danger to divers, it should be left uncovered wherever possible. Removing and replacing covers always takes diver time and may occasionally prove very difficult. Covers that are installed should therefore be designed so that they can be opened safely by a diver.

Overlap of the spheres of influence of intakes should be avoided if possible so that an individual intake can be worked on without a diver or ROV being affected by the water flow. Such isolation may be achieved by staggering intakes either horizontally or vertically.

Snagging

Anodes and other similar secondary attachments are potential snagging points for ROV tethers and diver umbilicals. ROVs are particularly susceptible to snagging, and to free an entangled line may require diver intervention when none was intended.

Wherever possible, all projections and attachments on a structure should be free from potential snagging points. Divers tend to swim along the tops of members and outside main legs, and attachments with the potential of causing snagging should therefore be on the underside of horizontal members wherever possible. In addition to the snagging risk, attachments on the sides of members tend to trap debris.

However, anodes fixed only on the undersides of members are unlikely to provide adequate corrosion protection, and Figure 10.5 illustrates two methods of detailing 'snag-free' anodes. The use of profiled anodes is increasing but more innovative configurations, such as the bracelet anode, may also be beneficial. Pad or bracelet anodes would significantly reduce the snagging hazard and provide the additional benefit of reduced hydrodynamic loading. Alternatively, the use of paint or other coatings to reduce the number of anodes required may become more acceptable if the advantages of easier and safer diver access are taken into account.

Navigation and orientation

The problems of navigation and orientation under water can be alleviated by attaching identification markers to a structure. Types of markers include:

- paint
- weld beads
- steel cut-outs
- GRP panels
- reflective markers
- fluorescent/luminous markers
- light modules (including beta emitters).

Proprietary systems are available, some incorporating anti-fouling agents, for attachment during fabrication and for retrofitting. The number and location of markers depends on the amount of underwater working envisaged but markers should be fitted to all structural members and joints whose failure would seriously endanger the whole installation. Depth markers can be fixed to structure legs and buoyancy tanks, and a grid identification system may be appropriate for large areas of plate. Permanent reference points for repeated thickness measurements and other non-destructive tests would also be helpful.

Navigation systems are available based on fixed hydrophones attached to the structure (see Section 7.4.5). The hydrophones should be located to ensure unobstructed signal paths to the diver or ROV. Whichever identification or navigation system is adopted, it should be laid out to suit the type of intervention to be used. The components of the system must be 'visible' in the direction from which the ROV or diver is deployed.

The results of a (stereo) photographic survey made while the structure is still in the fabrication yard would reduce some of the orientation problems of underwater inspectors. An extensive photographic survey prior to load-out can augment as-installed drawings by showing features such as construction aids and small details.

Rigging aids

Rigging time necessary to ensure the diver can maintain his position while working is a significant part of total diving operations at some locations. It may therefore be beneficial to detail permanent rigging attachments at points likely to be visited relatively frequently during inspection programmes or where inspection might be expected to be particularly difficult. The undersides of plated areas such as conductor guides fall into the latter category.

The provision of padeyes within the module support frame (MSF) offers the greatest flexibility for handling equipment and materials under water in the event of unforeseen inspection or repair. An installation may have a DDS with multiple lowering points to gain access to the whole structure but padeyes on the MSF rather than at each lowering point may be a more cost-effective solution. In either case, corresponding padeyes are necessary at the mudline. Guide wires for bell deployment can then be attached when work has to be carried out. Loading capacity of padeyes should be of the order of 5 tonnes.

A similar system could be incorporated to deploy diver-support platforms at appropriate points, eg at locations where temporary pile guides will later be removed. A suggested layout is shown in Figure 10.6.

Any rigging aids should be detailed to ensure they do not become snagging points (see 'Snagging' above).

Mooring points

Mooring points for DSVs should be provided on an installation, especially where it is intended to use air diving support vessels (ADSVs). Possible locations should be discussed with DSV operators and access would be required to the mooring points from the deck of the installation. Mooring arrangements should be designed for operation without the assistance of personnel from the installation.

10.3.2 Access for inspection

Conductors and risers

Access to conductor arrays has often been limited because of their close spacing. For effective access, there should be sufficient space between adjacent conductors for a diver (or ROV) to work with inspection and cleaning equipment. A space of at least 1 m has been suggested but 2 m, if achievable, is better.

Access problems arise when risers and J-tubes are fixed close to primary structural members in order to minimise environmental loading or the risk of accidental impact damage. Consideration could be given to increasing the stand-off between tube and supporting member (although the inevitable increase in the weight of supporting steelwork may not be acceptable).

Conductor guide cones and their gusset plates close to the edge of conductor frames have sometimes restricted access to the joints connecting the frames to the primary structure.

There should be adequate access to clamp bolts. The only way to check bolt tension is to twist the bolt head manually and, even then, marine growth may give the impression that a slack bolt is tight. When bolts are used, they should be as long as possible or employ positive locking.

Flanges, supports for conductors, etc should not be located in the splash zone.

External stiffeners

Gusset plates and external stiffeners at tubular joints reduce the length of saddle weld accessible for inspection. If such stiffeners are unavoidable, their shape and spacing should be fixed with access considerations very much in mind.

Anodes

The location of anodes or anode supports close to joints may prevent inspection of a significant length of the joint welds. It has been reported that anodes have actually been positioned across joints and over manholes and other possible crack initiators.

Grout and control lines

Although grout and control lines are usually only required during installation, they are seldom removed afterwards and often remain to create an access problem during later inspection operations. A removable truss carrying the temporary ducting and pipework has been used in some recent designs so that the main area of diving activity can be freed of this unnecessary obstruction. If such an arrangement is not used and control lines are to be left in place, they should be fitted into locations clear of areas likely to be visited by diver/ inspectors or ROVs.

Piles

The inspection of piles has received little attention in the integrity assurance debate despite the crucial role of the foundations to continuing structural integrity. Structural monitoring (see Section 10.3.3 below) may give some indication of foundation stiffness, but is not appropriate for localised inspection of individual piles.

The problem is one of access – external inspection is not possible and internal intervention is not usually catered for. The problem is exacerbated by the fact that the critical section of the pile in terms of potential fatigue damage and overstressing is at the mudline, yet it is not possible to detect through-wall cracks at this location because of the access restrictions. However, this is not a cause of great concern with conventional piled structures where the piles carry no significant tensile loads, only for structures such as TLPs and some guyed towers where tensile loads are substantial. It is suggested that through-wall cracks could be detected using pressio-detection as illustrated in Figure 10.7. Alternatively, the new technologies developed for intelligent pigging of pipelines could possible be extended for this application.

The installation of pressure meters along the length of piles could provide useful long-term indications of the soil-pile performance, providing the instrumentation continues to perform satisfactorily after installation.

Pigging

In view of the increasing use of intelligent pigs for pipeline inspection, their particular requirements should be considered at the detail design stage as well as the conceptual engineering phase (see Section 10.2.2).

Uniformity of pipeline bore is of primary importance to ensure satisfactory access. Although pigs can tolerate small circumferential steps (up to 2% of pipeline diameter, ie 15 mm for a 900 mm diameter pipe), a uniform bore improves vehicle dynamics and leads to more reliable results. Valve bores (not less than approximately 0.9 x the pipeline diameter), bend radii (at least 3 x diameter) and bores of branch pipelines should all be selected and designed with care. Branch pipeline bores equal in size to the main line can be tolerated, provided 'pig bars' are fitted and adjacent branch spacing should be greater than 1.8 m.

10.3.3 Structural monitoring

If a structural monitoring technique were allowed for in the detail design of an offshore installation, the necessary equipment could be fitted during fabrication at a much lower cost than for retrofitting. At this reduced price the techniques may prove to be more acceptable and they would thus gain the operational testing which is still required to match the extensive, and largely successful, development work which has already been carried out. At the same time, recent developments and successful offshore trials of hydro-acoustic telemetry [10.2] may result in cheaper and more reliable retrofitted systems.

See Section 7.5 for descriptions of the monitoring techniques available.

Vibration analysis

Vibration analysis can be carried out using deck-mounted accelerometers and standard environmental-data-gathering systems, and neither of these requires special consideration at the design stage. Deployment tubes for water particle velocity meters were designed into one recently fabricated structure.

Vibration analysis is particularly sensitive to changes in deck mass but it may be possible to overcome this shortcoming by continuous monitoring of the deck mass using load cells in the lower module supports. This would require extra design and fabrication effort but the benefits of a reliable weight-monitoring system would far outweigh the extra costs.

Flexibility monitoring

Although flexibility monitoring holds out considerable promise as an accurate method of locating brace failures, accelerometers are required at each level of bracing in a fixed steel platform. These and their associated cabling are expensive to retrofit but, if deployment tubes were attached to the structure during fabrication, measurements could be taken at any level using a single accelerometer package. This system has been used by one operator on a deepwater platform. At least half the legs require deployment tubes over their whole lengths, and diagonally opposed legs should be instrumented so that torsional vibration modes can be investigated.

Acoustic emission

Acoustic emission may gain acceptance for local monitoring at specific locations but, unless the locations requiring monitoring are known prior to fabrication (at cast nodes for example), transducers and associated cabling must be retrofitted at each location requiring monitoring. The retrofitting would be considerably cheaper if cable ducting were fitted during fabrication to all likely monitoring sites.

Strain and foundation monitoring

Strain monitoring is similar to acoustic emission monitoring in that data must be gathered from isolated locations. Strain gauges for retrofitting are available, and have been used for monitoring loads in repaired braces. As with acoustic emission, this would have been made easier if ducting had been fitted to likely damage sites during fabrication.

Attachments for foundation monitoring equipment such as piezometers should be designed and detailed to resist installation loads if damage is to be avoided at this early stage.

Cathodic protection monitoring

Sensors to measure cathodic protection potential should be located at critical locations – to ensure effective monitoring of areas where sufficient potential may not be achieved or where divers may find it difficult to make access with hand-held probes. The problems of cable runs must be solved if the sensors are to be interrogated using a conventional cable link; if a hydro-acoustic link is used there must be a clear 'line of sight' between sensors and the interrogating equipment.

10.3.4 Redundancy and defect tolerance

Redundancy and defect tolerance as design criteria can involve considerable analysis before failure mechanisms are identified, and this type of detailed and time-consuming analysis is difficult to fit into the design process. Fatigue analyses are also time consuming, but fatigue design and detailing are accepted without question as mainstream design activites (although based on simplified assessments). The redundancy and defect-tolerance study should be a checking and validation procedure; it should not radically change the design but should provide input to the inspection/maintenance philosophy for the structure.

10.3.5 Antifouling procedures

Antifouling methods are available to prevent or at least control marine growth on the surfaces of offshore installations. Some can be installed at the time of construction and some are suitable for retro-fit. Broadly, they can be divided into toxic and non-toxic methods. Toxic methods introduce biocides into the water surrounding the protected surface in sufficient concentration to repel, kill or impair the development of the potential foulers. Non-toxic methods make the surface unacceptable to the settling organisms by other means (for example by interfering with their adhesion) or by physically abrading them.

Toxic methods

Antifouling paints rely on the dissolution or leaching of cuprous oxide and/or triorganotin biocides for their effectiveness. The biocide in conventional antifouling paints is physically admixed with the organic binder and its rate of release declines exponentially. These paints have relatively short lifetimes and are therefore unsuitable for application to offshore installations.

Self-polishing copolymer paints contain organotin biocides which are chemically bonded with the binder. They mostly consist of tributyl tin methacrylate copolymerised with methylmethacrylate, and have a high content of toxic tributyl tin biocide (20–25% of the dry film weight). The biocide is released from the paint surface by hydrolysis on contact with seawater, while the remaining organic polymer is removed by the combined processes of dissolution and erosion. The processes of hydrolysis and dissolution/erosion are restricted to the surface of the film and the reaction proceeds until no polymer is left. For practical purposes the release rate of the biocide can be considered to be constant and the service life of the paint is thus inversely proportional to the erosion rate of the film and directly proportional to the thickness of the film. A 'high-build' coating with total film thickness greater than 500 μm could give protection on a static offshore installation for 5–7 years, although the performance of antifouling paints on offshore structures has never been rigorously tested. Prolonged tests on ships laid-up in harbour have shown that self-polishing copolymer coatings are effective against most plant and animal fouling organisms, but are ineffective against slime-forming bacteria and diatoms.

Freely corroding alloys of copper and nickel are toxic to fouling organisms if the copper content of the alloy is greater than 80%. Copper-resistant bacteria readily colonise the surface of the alloy, giving a surface film composed of layers of corrosion product and entrapped layers of bacteria and silt particles, but the upper layers of this film are loosely adherent and shear off easily, carrying away any attached fouling organisms and exposing fresh layers of toxic corrosion product on the surface. The exposed surface is then recolonised by bacteria and the cycle continues. Tests have shown 90/10 copper nickel alloy to give the best results and that its antifouling properties are unimpaired after 14 years exposure in flowing seawater; any fouling that does settle is likely to be malformed and loosely adherent. It has been used as a splash-zone coating on offshore installations (eg on the legs of the Morecombe Bay gas jackets), as a commercial marker system (see Section 10.3.1) and as a riser cladding. Lifetimes in excess of 20 years have been predicted for these materials. The copper nickel alloys can also be formulated in the form of polyester resins for spray or brush application to the structural surface. Test panels of this material have been exposed in seawater for eight years without maintenance.

Non-toxic methods

These are two commercially available antifouling coatings available in the UK that work by presenting a very slippery surface to potential foulers. They incoporate a non-toxic releasing oil in a porous silicone rubber matrix. The oil exudes slowly from the matrix to form a self-renewing, hydrophobic, low-friction surface. The longest duration test of this type of coating has been a 12-year exposure of a test panel in Newton Ferrers harbour. After this exposure the coating was largely free from fouling with a light attachment of slime and filamentous seaweed.

Antifouling hoops have been designed to give protection to horizontal and vertical tubular members. The hoops spiral along the member, driven by sea currents acting on articulated vanes mounted around the perimeters of the hoops. Friction between the hoop and the member is sufficient to remove settling fouling organisms. Commercially available hoops manufactured from polypropylene are currently under test on a number of steel offshore structures. It is estimated that between 500 and 1000 hoops would be needed to protect a typical northern or central North Sea jacket platform, protecting only straight members and running between obstructions such as nodes, anode stubs, etc. Hoops can be fitted to new structures or retro-fitted (after all the marine growth has been cleaned off the area to be protected). The lifetime of these hoops has yet to be determined and may depend on the lifetime of the antifouling coating that is used to protect the hoop itself.

Chemical/biological control

Although laboratory tests have shown that larvae can be prevented from settling on a surface by the application of non-toxic chemicals, no commercial product has been developed for this purpose.

It has long been speculated that suitably controlled competition among different fouling species may lead to a reduction in the cover of a troublesome species and the dominance of an acceptable, insignificant one. The best example of this is the competition between mussels, seaweeds and hydroids on platforms in the North Sea. It has been thought that cleaning off mussels at a particular time of year would promote the colonisation of seaweeds and hydroids, and so prevent or delay the resettlement of mussels. While some anecdotal reports seem to support the view that this does occur, at least in the short term, no rigorous study has been conducted to confirm it.

10.4 FABRICATION AND DESIGN CLOSE-OUT

Installation and hook-up represent the completion of the development phase of a design and the start of the operational phase. In many cases this change coincides with a change of responsibility within the operator's organisation – the project development team is disbanded and the involvement of the various design, fabrication and installation contractors comes to an end. Some operators do continue to involve the designer after installation, but this is by no means the norm.

A vast amount of valuable design data exists at this stage and it should be documented in a form suitable for retrieval and use during the installation's operational life. There are many examples of early North Sea structures where the detailed design and fabrication data is either not available to engineers responsible for inspection and maintenance or is not in a form suitable for use by them. The sections below propose a systematic method of preserving and presenting this data.

10.4.1 Design data for inspection planning management

Historically, structure design documentation has been directed towards obtaining certification, but operators have found data in this format difficult to interpret when defining inspection requirements or when assessing defects and modifications. It was clear from the survey of industry opinion conducted for this Project (see Section 1.3) that the majority of operators would like to have more information readily available from designers when setting up inspection programmes. The present situation, in which even fatigue lives are not always accessible, is due to the absence of a co-ordinated approach to inspection-related problems. With a little extra effort, the data requirements of inspection engineers could be satisfied at the design stage.

The method of presentation of the conventional detailed documentation of the design calculations, fabrication data, results from installation and in-service inspections, etc is dependent on the facilities and systems of the individual operator. But, whatever method is used, it should be possible to retrieve data such as member forces and material certificates.

10.4.2 Extra documentation

It is important that the engineers responsible for the inspection and maintenance of an installed structure are aware of the design criteria used and any intended limitations. It is also important to realise that the individual engineers responsible for the structure may well change during its operational life. The need therefore is for documentation that any competent engineer can use quickly to determine the basis of the design and recall the history of fabrication of the structure, its installation and operation to date. To reach these objectives, the documentation should be defined with adequate consultation between all the parties involved on the design and operational sides.

Two documents in addition to those required for certification would fulfill this requirement:

- *A design, fabrication and installation dossier* (such as the DFI resume of the Norwegian Petroleum Directorate). The dossier should contain a concise description of the design, fabrication and installation phases, together with all basic data, summaries of calculations and other design documentation. It should make full references to relevant detailed documentation.
- *An inspection and maintenance manual.* This should contain the design recommendations for inspection, including the basic philosophy. It should be considered an essential document for structures where a particular inspection philosophy is included as a basic design criterion.

Note that both these documents should be kept 'live' during the life of the structure. Additional data from structural reappraisals, modifications and repairs should be incorporated in the design dossier. Summaries and results of inspections carried out should be added to the inspection manual.

10.4.3 Design data input to the inspection programme

The extent of design data required by inspection engineers for the formulation of an inspection programme will depend on whether or not the installation has been designed from the outset for a specific level of inspection. In either case, the data should be presented as clearly as possible, and with sufficient references so that any more detailed back-up documentation can readily be retrieved.

For a design based on a philosophy requiring a specific inspection effort (eg the fail-safe approach of Section 2.8.4) the designer should provide data on:

- the basic philosophy and its derivation
- critical parts of the structure which require special attention during inspection
- frequency of inspection
- the detail of the inspection required at the critical locations
- if structural monitoring is to form the basis of the inspection programme, consideration should also be given to providing a computer model for correlation purposes.

Where an operator does not wish to be limited to a specific inspection programme, the designer should supply sufficient data for the operator to formulate or redefine an inspection programme. This should include:

- fatigue lives
- member criticality as derived from redundancy or collapse analyses
- the defect tolerance of nodes with critical] fatigue lives or low redundancy
- member and joint utilisation on the basis of allowable stresses
- acceptable levels of foundation scour, marine growth and corrosion.

Data from the fabrication and installation phases is also required and the designer may have some influence on how this information is recorded and presented. It is important to record:

- welding data and trials
- mill certificate data (and the location of the relevant plate on the structure)
- any deviations from the fabrication or installation specifications
- any modifications carried out
- any design or site queries
- all fabrication defects (repaired or unrepaired)

- any installation damage and the nature of the repairs
- items removed during installation.

10.4.4 Input for damage assessment

Design data is also needed for the assessment of defects which arise during the operational life of a structure (see Chapter 8). The defects may occur from environmental loading or human interference (eg dropped objects or ship collisions). Whatever the cause, the operator should be able to make a rapid assessment of the consequences of the damage to the integrity of the installation.

Colour-coded drawings similar to those in Figures 10.8 and 10.9 would enable a first assessment to be made by untrained personnel. Access to the original computer model of the structure would be necessary to make a structural reassessment or reanalysis in response to failures. A well-documented computer model (structural reanalysis system) should be considered so that reanalysis of the structure can be performed at any time, thereby enabling emergency situations such as impact damage or other structural failures to be investigated with minimal delay. See Chapter 8 for details.

Table 10.1: *Summary of inspection-related design activities detailed in Sections 10.2 – 10.4*

Basic design criteria	Conceptual engineering	Detail design	Fabrication and design close-out
Target fatigue lives Redundancy	Structural configuration – redundancy – fatigue – framing geometry	Structural design – joint detailing – positioning of connectors and supports	Design documentation certificates – calculations – drawings
Permissible damage Diving systems Pigging requirements Replaceable items Marine growth profile	Positioning of equipment – diver deployment system – pig traps – risers/caissons – replaceable items Ease of access – joint details – location of equipment Review of the concept by operations and inspection engineers	Analysis – detailed failure/ redundancy assessment – fatigue analysis Diver aids – design of diver deployment system – structural marking – rigging attachments Provision for structural monitoring – primary system – secondary failure monitoring – weight monitoring system	Fabrication records – mill certificates – structural changes – welding/repair records – installation reports – as-built dimensions – photographs – NDT records – departures from specification – site queries Inspection/maintenance manual – inspectable items – criticality ratings – inspection periods – consequences of damage – structural monitoring programme

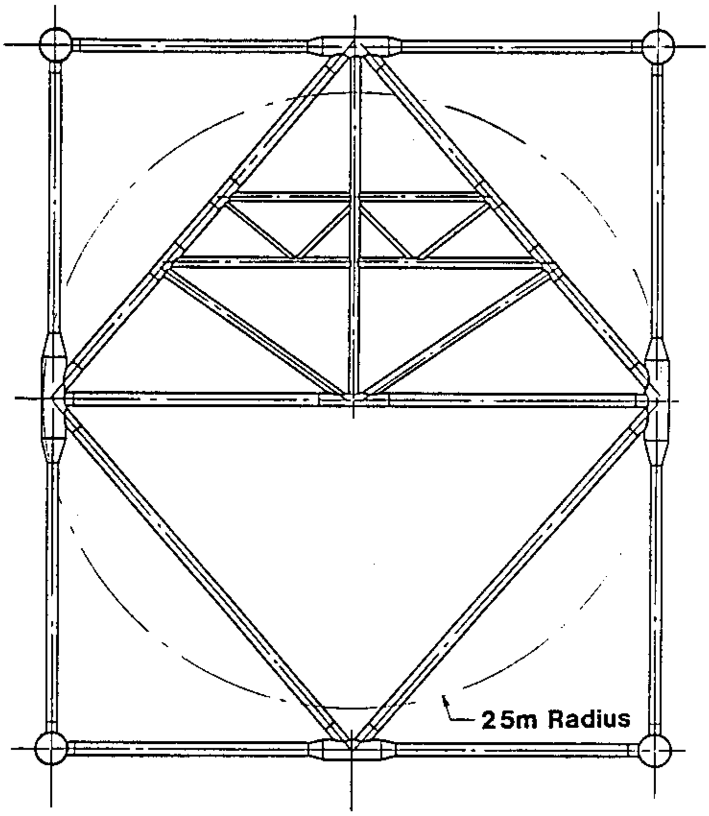


Figure 10.1: *Structure coverage from a single-point DDS*

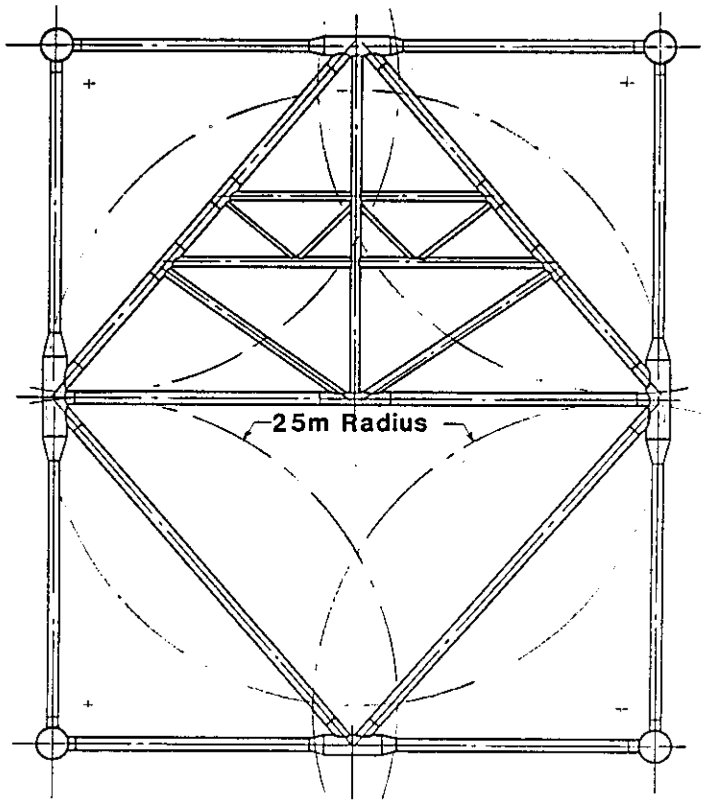


Figure 10.2: *Structure coverage from a multipoint DDS*

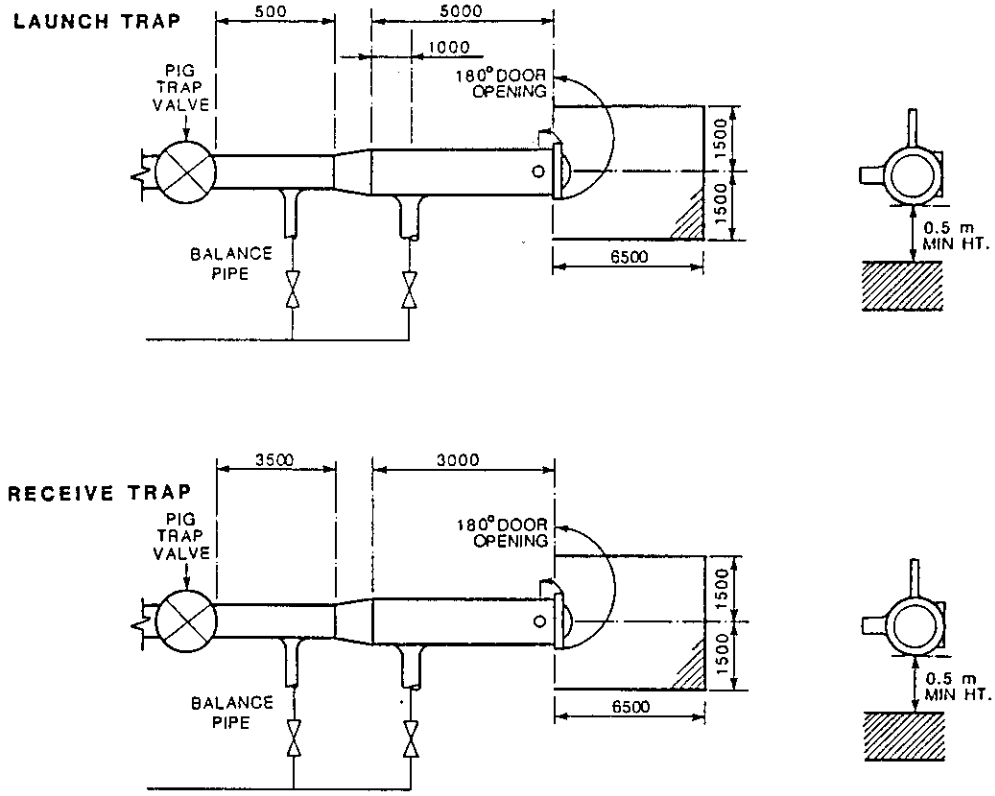


Figure 10.3: *Typical pig trap dimensions for 900-mm diameter pipeline*

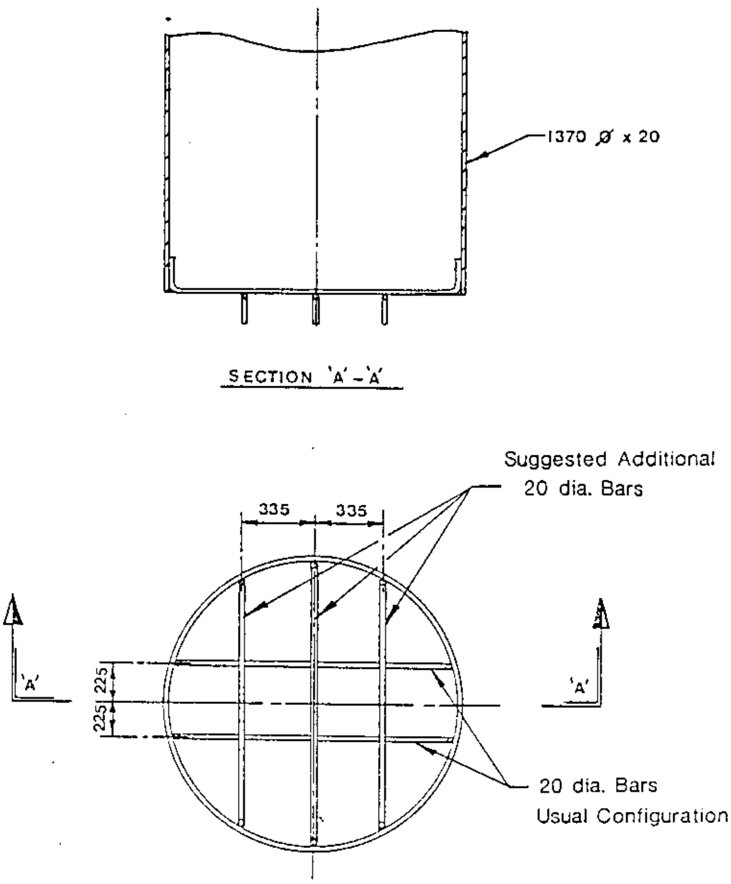


Figure 10.4: *Intake catch grid*

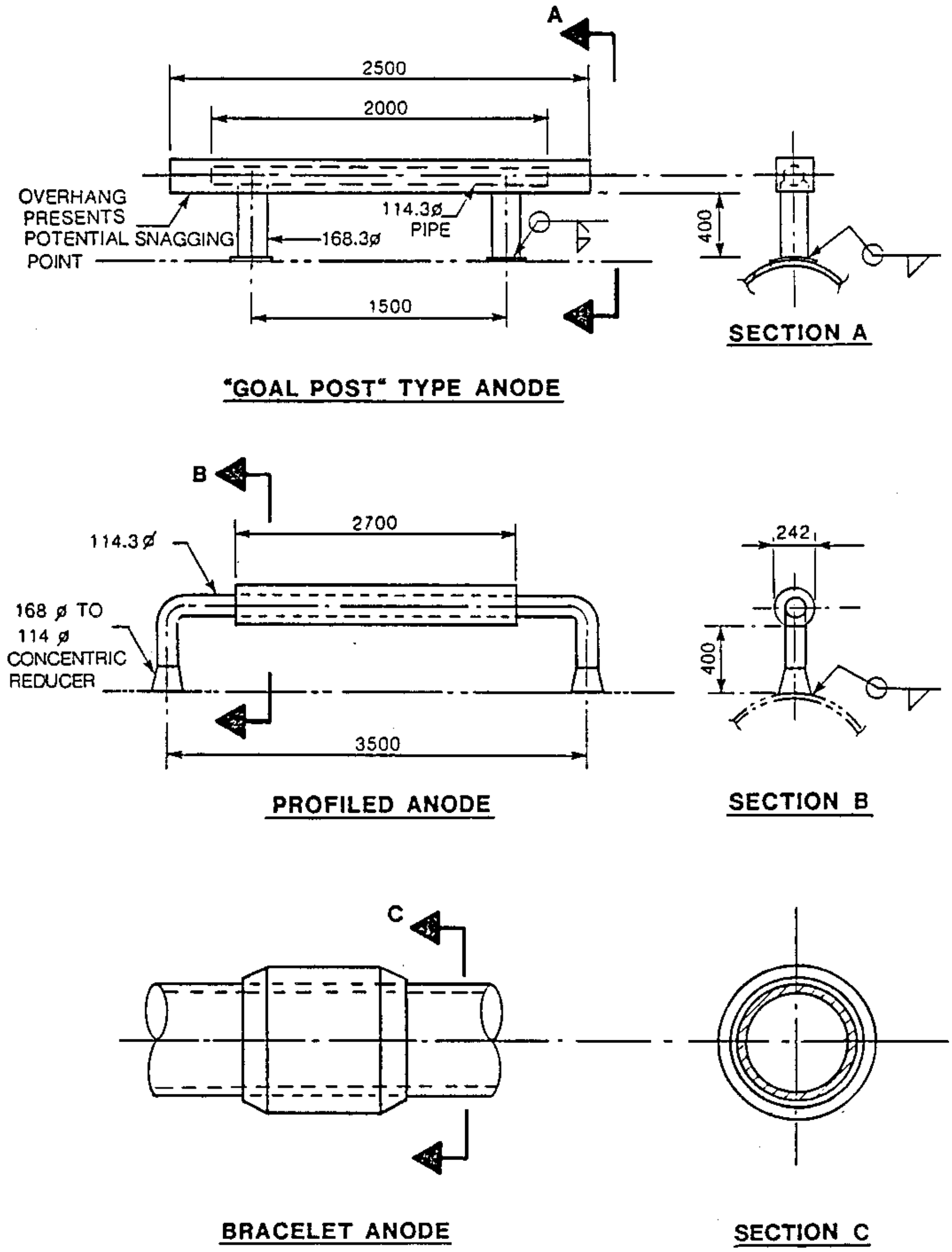


Figure 10.5: *Anode configurations*

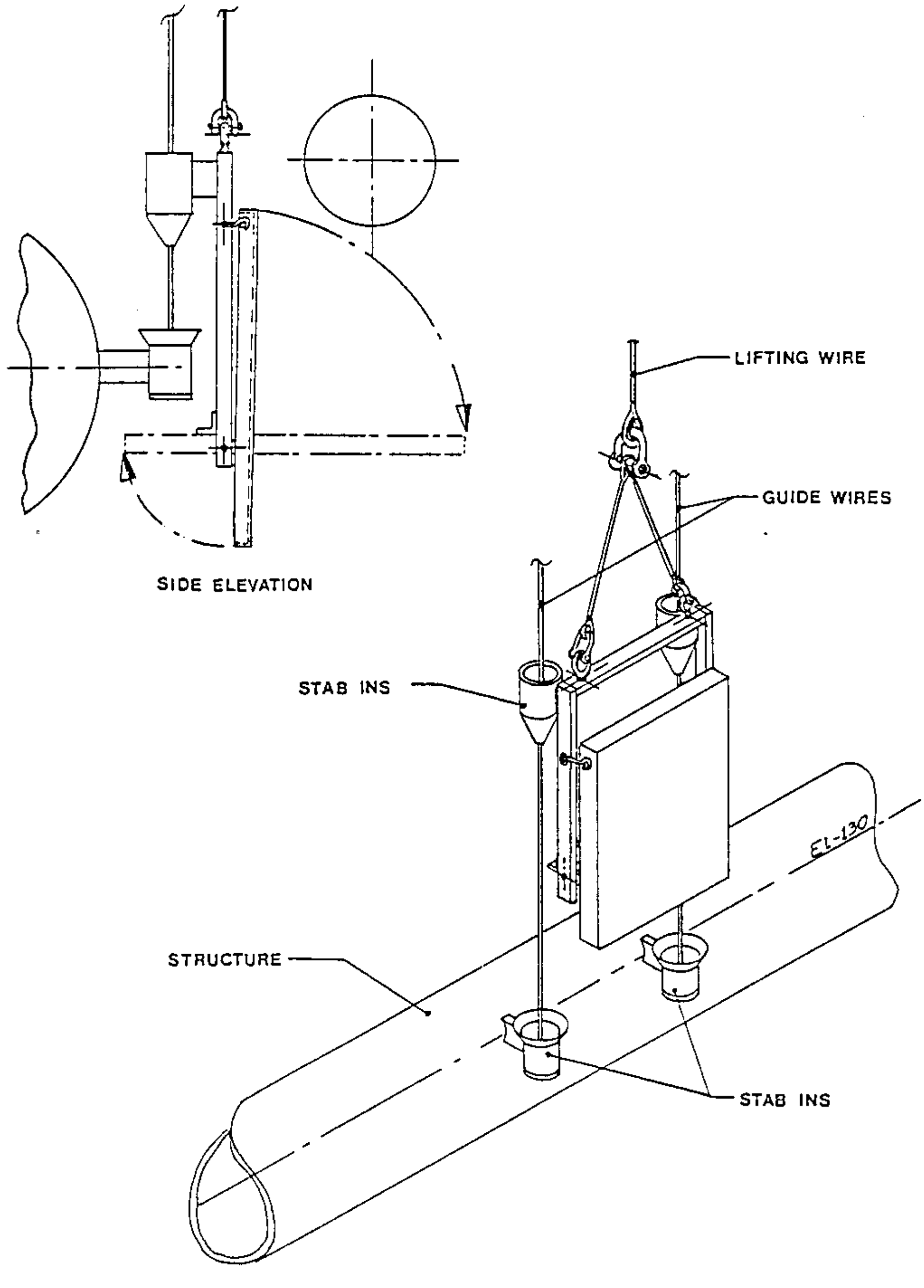


Figure 10.6: *Layout for diver work platform*

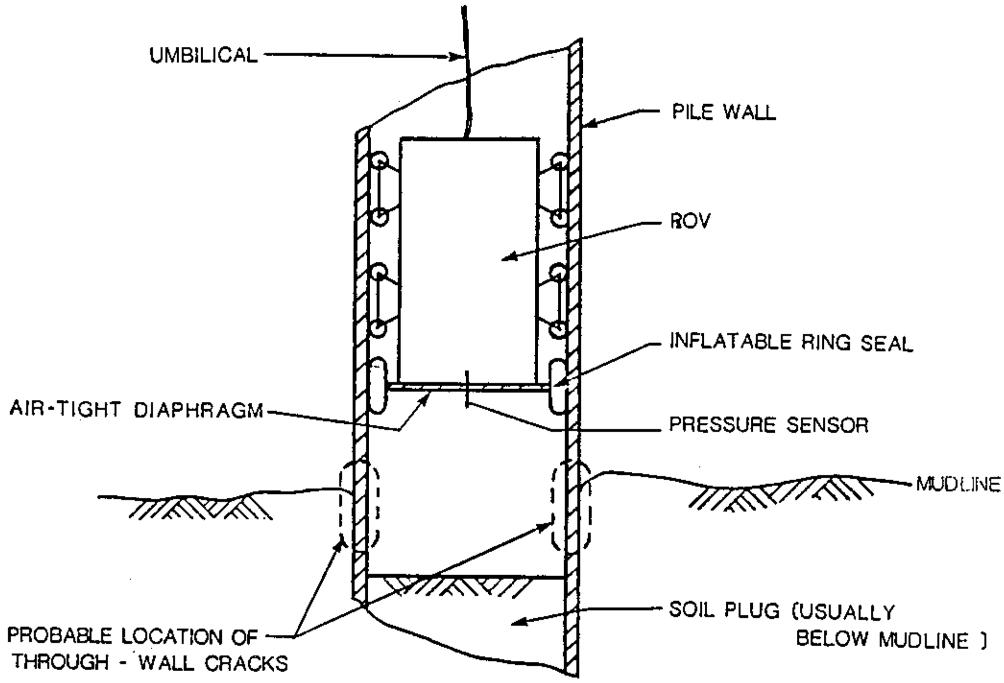


Figure 10.7: *Pressio-detection of through-wall cracks in piles at the mudline*

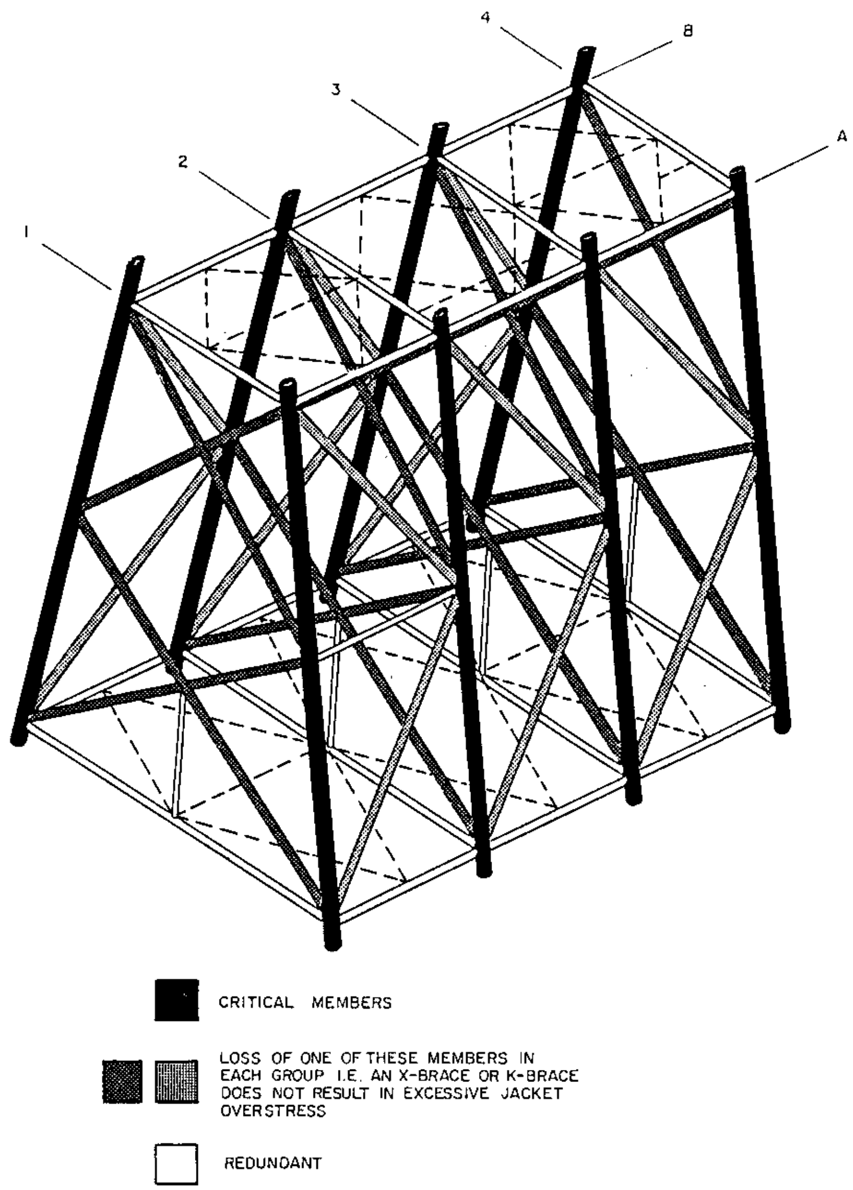


Figure 10.8: *Example of structural member redundancy diagram to be used by untrained personnel*

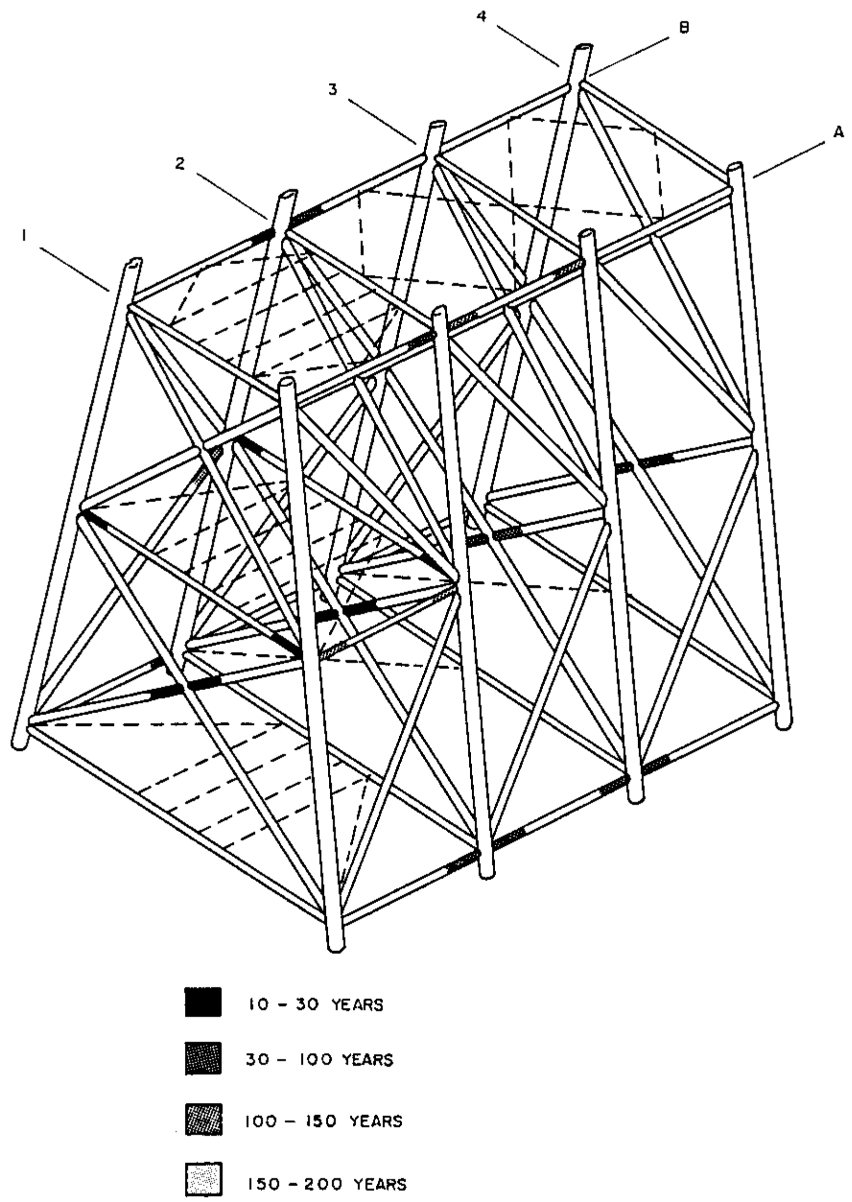


Figure 10.9: *Example of designed fatigue life diagram*

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Appendix 1: Statutory requirements, certification and guidance

Statutory requirements to inspect offshore installations (see Section 2.2 of the main report) provide a minimum framework within which inspection programmes must be developed and with which they must comply. The Governments issuing the requirements also make available non-mandatory guidance documents to give more information on inspection planning and techniques, and other central organisations issue standards and codes of practice covering some of the techniques used for underwater inspection. The requirements, guidance and standards differ from country to country. The list below does not include all countries with offshore interests or all certifying authorities, but it is representative of current requirements.

Because of the range of types of installations, all the published documents inevitably contain overall requirements and broad guidelines. One frequently recurring requirement is that the operator and appointed certifying authority should agree an inspection programme for each installation. In developing this programme, it is essential to refer to the documents themselves – the information given below is only in the form of brief comparative summaries.

A1.1 UNITED KINGDOM

The statutory requirements and certification procedures for fixed and mobile offshore installations located in UK territorial waters are described in the 'Mineral Workings Act 1971'[A1.1]. The requirements for submarine pipelines are contained in the 'Petroleum and Submarine Pipelines Act 1975[A1.2]. Both of these Acts have subsequently been extended and amended by the 'Oil and Gas (Enterprise) Act 1982'[A1.3].

Statutory Instruments have been issued through the Acts, to describe the Government's requirements in more detail:

- 'The Offshore Installations (Construction and Survey) Regulations 1974', SI 1974 No 289[A1.4] covers offshore installations
- 'The Submarine Pipelines Safety Regulations 1982', SI 1982 No 1513[A1.5] covers offshore pipelines.

The Department of Energy interprets these Statutory Instruments to produce guidance on the required technical standards and procedures. In this manner, the statutory requirements can be kept up to date with operational experience and developing technology without the need to refer back to the UK Parliament.

The UK Secretary of State for Energy has appointed six certifying authorities to issue Certificates of Fitness. It is the responsibility of an operator to apply for a Certificate of Fitness from one of these certifying authorities before starting operations. Some of the certifying authorities have issued their own guidance rules for the design, construction and inspection of offshore installations (see Section A1.4 below). These facilitate their assessments of installations, as well as providing guidance for operators and their engineers on the standards required.

A1.1.1 Fixed offshore installations

The Department of Energy's certification procedures for offshore installations are summarised in Figure A1.1.

SI 289[A1.4] describes the minimum requirements of the individual certifying authorities in UK waters. Extracts from the Statutory Instrument indicate the main requirements:

> **"Certification of Offshore Installations**
>
> **3.**(1) On or after 31st August 1975:
>
> (a) no fixed installation shall be established in the relevant waters;
>
> (b) no mobile installation shall be brought into those waters with a view to its being stationed there; and
>
> (c) no fixed or mobile installation shall be maintained in those waters;
>
> unless there is in force in respect thereof a valid Certificate of Fitness.

"**8.**(1) In respect of every offshore installation in relation to which there is no Certificate of Fitness in force or in respect of which a Certificate of Fitness is in force and a renewal thereof is sought, there shall be carried out a survey (herein referred to as a 'major survey') which shall include a thorough examination of the installation and its equipment . . .

"**8.**(2a) In respect of every installation in relation to which a Certificate of Fitness is in force, there shall be carried out on behalf of the Certifying Authority which issued that certificate, surveys (hereinafter referred to as 'annual surveys') of a selection of the members, joints and areas of the primary structure of the installation . . ."

In addition:

- a Certificate of Fitness may be issued for a maximum duration of five years
- a Certificate of Fitness may be withdrawn by the Department of Energy, but not by the Certifying Authority
- re-certification is required at least every five years upon issuance of a new Certificate of Fitness.

The Department of Energy's publication 'Offshore installations: Guidance on design and construction'[A1.6] gives more detail and requires that the *annual survey* should "ensure that any deterioration of the structure is within acceptable limits". It should include the following:

- close visual inspection down to and including the splash zone
- assessment of the thickness of marine growth
- further inspections and/or non-destructive tests as required
- close examination of any repair work undertaken since the last survey
- where scour is known to be a problem, the inspection should include the condition of any permanent scour prevention works.

Major surveys are required for renewal of a Certificate of Fitness, ie recertification. The inspection schedule should take account of regions in which defects are most likely to occur, and areas which are highly stressed or are subjected to severe fatigue loading. The second *annual survey* after each *major survey* should include a general inspection of major parts of the installation below the splash zone. Additional surveys should be performed where the structure may be affected, either locally or as a whole, by alteration, deterioration or damage.

The requirements of a major survey are often spread over tha annual surveys. Then, completion of the final annual survey satisfies the requirements of the major survey.

A1.1.2 Mobile offshore installations

The Department of Energy Guidance Notes[A1.6] are applicable to all installations as defined by the Oil and Gas Enterprise Act 1982. Most of the points discussed above are therefore also valid for floating units. One additional requirement for mobile units is that: "If practicable, the second annual survey of a mobile installation should be carried out in sheltered waters; all other annual surveys may be carried out on location when weather conditions permit".

All of the guidelines for mobile offshore installations recommend that a 'construction portfolio' should be prepared for each unit, summarising its history and including information such as as-built reference drawings and steel properties, together with a detailed inspection programme.

A1.1.3 Submarine pipelines

The certification procedures for submarine pipelines are summarised in Figure A1.2. Pipeline certification is typically carried out by the Pipeline Directorate of the Department of Energy but can be delegated by them to a Certifying Authority. The Pipeline Directorate, Certifying Authority and operator usually meet to agree on lines of demarcation.

SI 1513[A1.5] describes the safety regulations for submarine pipelines, and includes a requirement for inspection schemes. The powers of inspectors are defined in SI 1977 No 835[A1.7]. Extracts from SI 1513 indicate the main requirements for pipeline inspection and monitoring:

"**4.**(1) There shall be at all times in force in respect of all parts of a controlled pipeline a scheme (in this Regulation referred to as the 'inspection scheme') providing for their systematic examination and, in respect of apparatus and works for securing the safe operation of the pipe-line associated with the pipe or system of pipes comprised in the pipe-line, testing, at intervals not exceeding 12 months.

"(5) Such examination shall as far as is reasonably practicable, be capable of revealing:

(a) any damage to, or defect in, the pipe-line;
(b) any change in the position of the pipe-line;
(c) the extent to which the pipe-line is covered by soil or other material;
(d) the condition of the seabed in the vicinity of the pipe-line; and
(e) the extent of marine growth on the pipe-line.

"(6) Such testing shall, so far as is reasonably practicable, be capable of revealing any defect in the operation of the apparatus and works for securing the safe operation of the pipe-line associated with the pipe or system of pipes comprised in the pipe-line . . ."

As with offshore installations, the Department of Energy has published further guidance, namely the 'Submarine Pipelines Guidance Notes'[A1.8]. On the subject of operational requirements the Department asks for details of method of leak detection, of pig launching and receiving facilities and of monitoring and controlling external and internal corrosion. Designers should also consider "additional protection from environmental and human hazards such as heavy trawling equipment".

The operator should produce a description of the programmes for maintenance and inspection of pipelines and risers. He should include internal inspection, corrosion control, cathodic protection measurements and bottom surveys in the description.

A post-construction survey is required of the entire pipeline "as soon as practicable following construction". The main objectives of this survey are:

- to permit the 'as-built' co-ordinates of the pipeline to be fixed
- to check trenching or burying
- to check for unsupported lengths of pipeline
- to examine the overall condition of the pipeline
- to check for debris.

For the *12-monthly inspection* scheme referred to above, a two-tier inspection of the pipeline is permitted: a preliminary examination followed by further inspection determined from the findings of the preliminary inspection. The 12-monthly inspections should be "capable of determining, where relevant, as far as reasonably practicable:

- movement of the pipe
- unsupported spans
- loss of cover in buried lengths
- loss of weight coating
- damage to pipe
- excessive marine growth
- internal condition of pipe
- condition of corrosion protection system."

Specially vulnerable areas are to be examined in more detail and additional requirements are identified for risers. Over a number of annual inspection cycles, further more detailed inspection should be carried out to "provide a systematic record of changes in pipeline and surroundings enabling a judgement of its continuing fitness for use to be made".

Each pipeline should have an integrity monitoring system capable of monitoring and measuring corrosion and detecting leaks. Internal examination using an on-line inspection tool should be considered.

A1.2 NORWAY

The Norwegian statutory requirements for the inspection of offshore installations are specified in the Royal Decree 'Regulations for Production etc of Submarine Petroleum Resources', of 9 July 1976. These are expanded in the Norwegian Petroleum Directorate Guidelines[A1.9], which are applied primarily to fixed installations.

The procedures adopted in Norwegian waters are outlined in Figure A1.3.

It is the responsibility of a licensee to institute a comprehensive system of internal control to ensure that equipment and operations used in petroleum exploration and production are designed, manufactured and utilised in accordance with a comprehensive quality control programme and in compliance with the specific requirements of the NPD. Licensees may not delegate this ultimate responsibility to any third party, although they may obtain assistance form third parties in implementing their programmes of internal control. A classifi cation society may therefore offer assistance to licensees and owners of mobile drilling units as a third party but these services are not carried out 'on behalf of the NPD,' they in no way replace the licensee's responsibility for instituting and maintaining internal control, and they do not 'ensure compliance' with NPD's requirements. The services are simply an assistance to the licensee in implementing his programme of internal control. The NPD alone has the authority for determining whether or not the internal control exercised by the licensee is adequate and appropriate for conducting operations on the Norwegian offshore continental shelf.

There is no certificate analagous to the UK Department of Energy Certificate of Fitness. An installation is evaluated as a part of an overall field development plan.

A1.2.1 Offshore installations

The NPD Guidelines follow a similar philosophy to the DnV Rules (see Section A1.4) for inspection of offshore installations except that the licensee is required to work within a four-year programme of inspection, not a five-year one. The Guidelines apply to various types of installations; there are no specific inspection requirements for fixed or mobile units.

A1.2.2 Submarine pipelines

The NPD Guidelines divide the inspection of underwater pipelines and risers into two areas – within the safety zone where the pipeline is not buried, and elsewhere. (A safety zone extends 500 m from the outermost point of any permanent or temporary oil and gas installation or equipment.) In each area, there are three types of inspection:

- *Initial*
  The initial inspection should be sufficient to confirm that the condition of a pipeline as installed is in accordance with the design assumption. Outside the safety zone, it should normally include inspection to detect free spans and mechanical damage and to measure depth of burial if appropriate.
- *Start-up*
  A start-up inspection is required to ensure that the pipeline can safely be put into operation. It should normally include:
  - mapping of depth of burial
  - detection of free spans
  - measurements of the distances between possible mechanical couplings and concrete coating
  - mapping of pipeline protection level
  - internal NDT following start-up.

  Pressure testing is mandatory and, within the safety zone, movements and behaviour should be monitored during start-up to ensure safe operation of the installation.
- *Annual*
  Annual inspections are based on the results and experience of previous inspections. Within the safety zone they should normally include:
  - mapping of possible damage
  - cathodic potential measurements
  - control of clamps, bolts and flanges
  - control of axial and lateral position
  - control of condition of seabed, including scour and free spans
  - visual inspection of marine growth
  - visual inspection of any fender device in the splash zone.

  In addition, dimensional readings on selected anodes should be made every four years. Internal inspection for detection of corrosion, change in pipe diameter, etc may be required. For pipelines outside the safety zone, the annual inspection should include inspection as recommended for start-up, together with inspection for corrosion and internal inspection to locate changes in pipe diameter. The need for NDT should be evaluated each year.

A1.3 OTHER COUNTRIES

It was not part of the scope of the project that led to this publication to compare the statutory inspection requirements of all countries with offshore interests. However, some details were readily available from two other countries.

A1.3.1 Denmark

The certification procedures in Danish territorial waters are based largely on Norwegian philosophy. As in Norwegian waters, the operator is responsible for self-certification and for obtaining third-party verification as necessary.

A1.3.2 Netherlands

The Dutch Ministry of Mines recognises the major classification societies and their rules for certification of structures on the Dutch continental shelf. Three certificates must be issued for an offshore installation in Dutch waters. They are:

- *Certificate of Design* – this states that the structure has been satisfactorily reviewed for compliance with the pertinent sections of the Mining Regulations 1964 and classification society Rules
- *Certificate of Supervision* – this states that the construction of the structure has been carried out under the surveillance of a classification society to approved drawings
- *Certificate of Fitness* – this states that the structure has been installed in accordance with the Mining Regulations under the surveillance of a classification society.

The Rules of the Dutch Ministry of Mines require that platform structures must be certified or classed by a recognised classification society. Pipelines, production facilities and equipment are not usually delegated to the classification societies; their certification is handled by the government itself.

A1.4 CERTIFYING AUTHORITIES

In addition to the statutory requirements and guidance published by national Governments, certifying authorities and other engineering organisations publish Rules and recommendations covering inspection of offshore installations of all types. The two certifying authorities with the most detailed Rules are Det norske Veritas and the American Bureau of Shipping. In addition, DnV have published a number of relevant Technical Notes that have now been re-designated as 'Recommended Practices'[(A1.11–14)].

A1.4.1 Det norske Veritas

Fixed installations

For fixed offshore installations, the DnV 'Rules for the design construction and inspection of offshore structures'[(A1.15)] require a long-term survey programme to be scheduled so that the whole structure is covered in a period of five years. The frequency of periodic surveys is to be evaluated for each installation, and the extent of each survey is to be based on accumulated evidence from previous surveys. The importance of planning for in-service inspection at the design phase is stressed – to consider ease of access, means of inspection, inspection frequency and identification of "significant areas". The surveys themselves should include:

- general visual inspection of selected parts of the structure
- close visual inspection and NDT of selected local areas
- inspection to check effectiveness of corrosion protection systems
- inspection to check the condition of the foundation and of any scour protection systems
- assessment of the amount of marine growth.

Submarine pipelines

For submarine pipelines, the DnV 'Rules for submarine pipeline systems'[(A1.16)] require annual inspections unless otherwise agreed, although continuous inspection may be acceptable. The operator should produce a description of the inspection programme, which should include:

- detection of free spans
- detection of exposed sections
- detection of mechanical damage and coating damage
- anode consumption and condition
- condition of seabed
- signs of lateral and axial movement
- detection of leaks
- thickness measurements (in suspect areas).

Subsea installations

The DnV guidelines 'Safety and Reliability of Subsea Production Systems'(A1.17) contain information on periodic inspection of subsea installations. An inspection manual is required which identifies inspection, maintenance and testing tasks, describes the procedures, sequences and frequency of inspection, testing and maintenance, and identifies the means by which inspection and maintenance should be carried out. Checks should be considered for the corrosion protection system and detection of damage from accidental loadings, debris, marine growth and scouring. The inspection programme should be based on a failure effect analysis of the installation, but surveys should be carried out at least twice within the five-year certification period. Any subsea installation fabricated and operated according to these guidelines receives a "statement of compliance", which satisfies the third-party verification required by the Norwegian Petroleum Directorate (see Section A1.2).

A1.4.2 American Bureau of Shipping

Fixed installations

The ABS 'Rules for building and classing offshore installations'(A1.19) have been applied in the Dutch sector of the North Sea and world-wide. Annual surveys are required, together with a special survey once every five years. Alternatively, a system of continuous surveys may be acceptable. Inspection may also be required following incidents that may have adversely affected the stability, integrity or safety of the structure. For the periodic surveys:

- Each annual survey is to include a thorough visual examination of all the above-water structure, with special attention to the splash zone for possible corrosion damage. "Additionally, where it appears that substantial deterioration or damage has occurred to an installation since the last survey, a general examination, by diver, underwater camera, submersible, or other suitable means, of the underwater structure, the sea floor and the corrosion control system shall be carried out." Modifications or repairs made as a result of findings at the previous survey should be given particular attention.
- The special periodic surveys require an annual survey plus "underwater inspection of selected areas of the installation . . . unless documented experience shows this to be unnecessary". Non-destructive testing is required on "representative structures, conductors and risers in the splash zone and elsewhere".

Mobile installations

The ABS 'Rules for building and classing mobile offshore drilling units'(A1.20) require annual surveys plus special periodical surveys at four-yearly intervals. A system of continuous survey may be undertaken whereby the special survey requirements are carried out in regular rotation. An examination of the underwater parts of each mobile unit is required at intervals not exceeding two-and-a-half years, by drydocking or (if the unit is not over 15 years old) by underwater inspection.

At each annual survey, a general examination is to be made of the exposed parts of the hull, deck, deck-houses, structures attached to the deck, derrick substructure and other items as applicable.

The special survey requires compliance with the annual survey and drydocking requirements, plus possibly internal and external examination, thickness gauging, and non-destructive testing.

Publications

Other ABS publications are included in the reference list as References A1.21 to A1.28.

A1.5 REFERENCES

A1.1 Mineral Workings (Offshore Installations) Act 1971, Chapter 61
HMSO

A1.2 Petroleum and Submarine Pipelines Act 1975, Chapter 74
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HMSO

A1.4 The Offshore Installations (Construction and Survey) Regulations 1974
Statutory Instrument Number 289, HMSO

A1.5 The Submarine Pipe-Lines Safety Regulations 1982
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A1.7 The Submarine Pipe-lines (Inspectors etc) Regulations 1977
Statutory Instrument Number 835, HMSO

A1.8 Department of Energy
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Guidelines for the Inspection of Primary and Secondary Structures of Production and Shipment Installations and Continental Shelf Legislation, 1983

A1.10 Dansk Ingeniorforening
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Recommended Practice, RP 704, 1983

A1.12 Det norske Veritas
Monitoring of Cathodic Protection Systems
Recommended Practice, RP B403, 1987

A1.13 Det norske Veritas
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A1.14 Det norske Veritas
Qualification of ROVs for Underwater Inspection
Recommended Practice, RP B706, 1983

A1.15 Det norske Veritas
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A1.18 Det norske Veritas
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A1.19 American Bureau of Shipping
Rules for Building and Classing Offshore Installations, Part 1: Structures, 1983

A1.20 American Bureau of Shipping
Rules for Building and Classing Mobile Offshore Drilling Units, 1985

A1.21 American Bureau of Shipping
Guidelines for Building and Classing Undersea Pipeline Systems and Risers

A1.22 American Bureau of Shipping
Guidelines for Building and Classing Facilities on Offshore Installations

A1.23 American Bureau of Shipping
Rules for Building and Classing Underwater Systems and Vehicles, 1979

A1.24 American Bureau of Shipping
Rules for Building and Classing Single Point Moorings, 1975

A1.25 American Bureau of Shipping
Guide for the Certification of Offshore Mooring Chain

A1.26 American Bureau of Shipping
Guide for the Lay Up and Reactivation of Mobile Offshore Drilling Units

A1.27 American Bureau of Shipping
Guide for Underwater Inspection in Lieu of Drydocking Survey

A1.28 American Bureau of Shipping
Guide for Certification of Drilling Systems

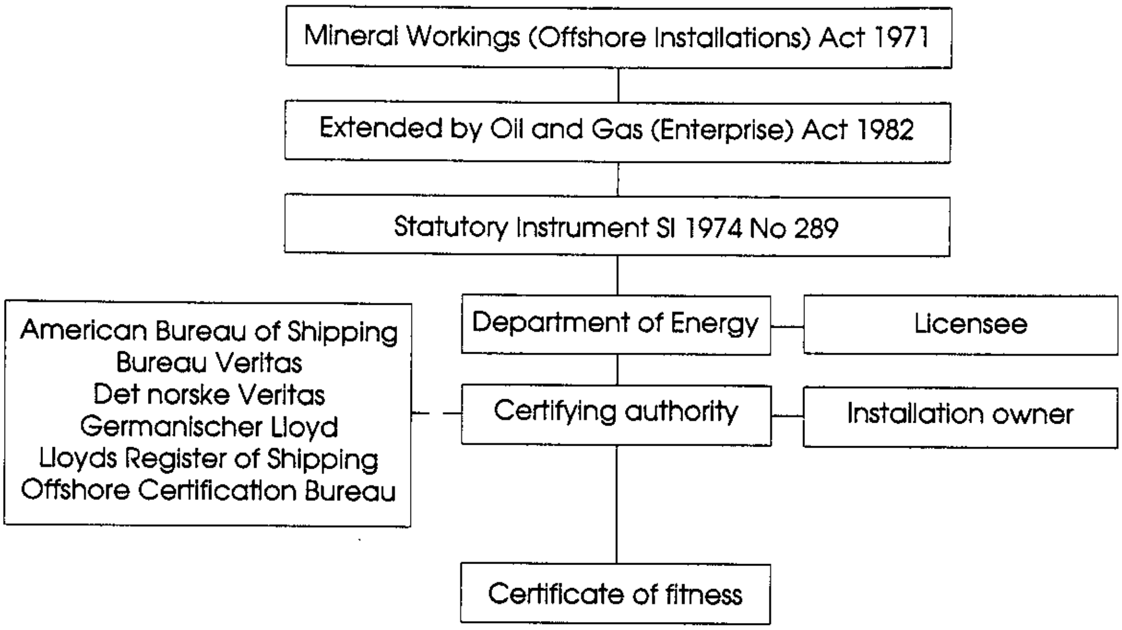

Figure A1.1: *UK certification procedures for offshore installations*

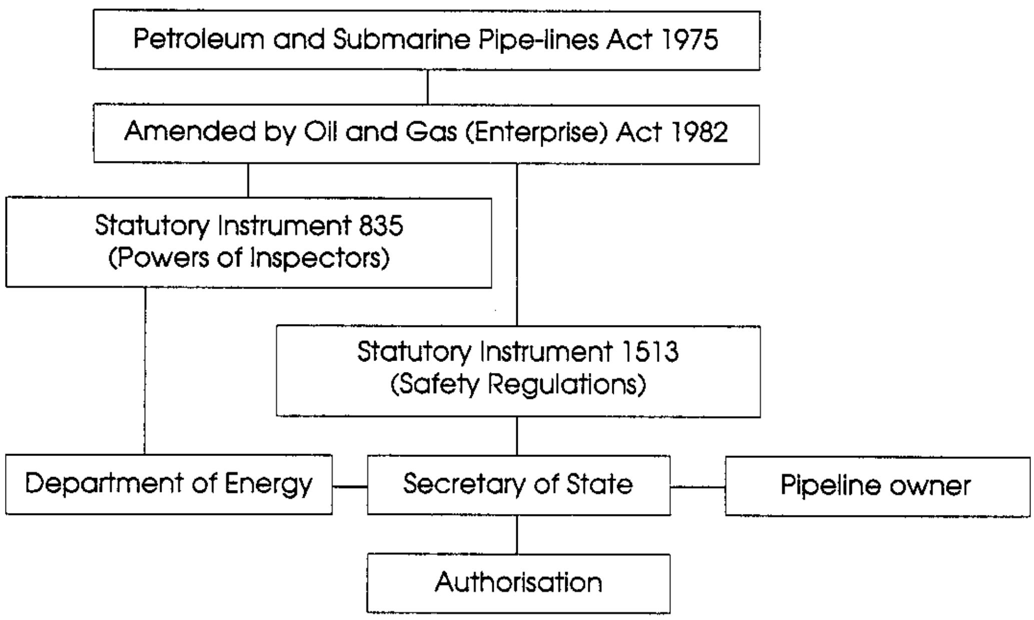

Figure A1.2: *UK authorisation procedure for submarine pipelines*

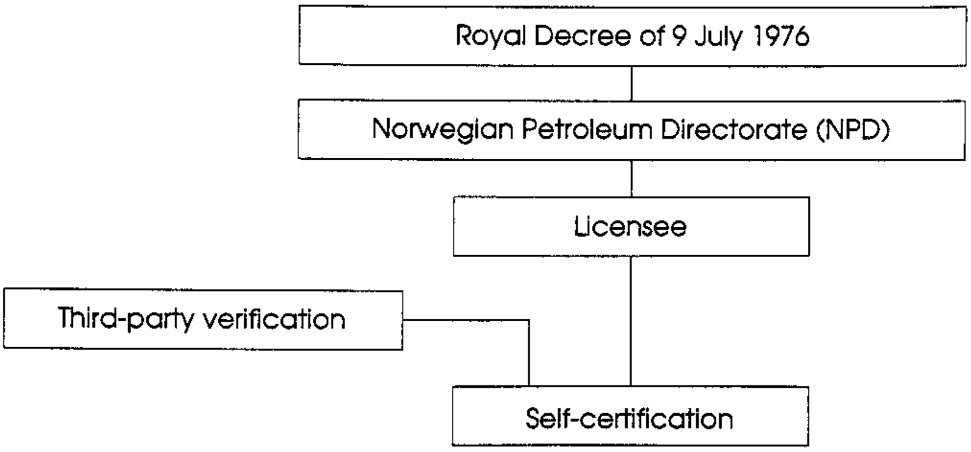

Figure A1.3: *Norwegian certification procedures for offshore installations and submarine pipelines*

Appendix 2: Principles of probabilistic techniques

This appendix is a short introduction to probabilistic techniques with particular reference to the application of this approach to reliability analysis. The treatment is necessarily brief and the interested reader is referred to References A2.1-3 for a rigorous treatment of this topic. It is hoped that this appendix provides sufficient background for an understanding of the potential benefits of the probabilistic approach to inspection planning.

A2.1 BASIC CONCEPTS

For each physical parameter in a structural analysis, such as total load on a member or stress at a hot spot, a value s may be measured at a particular time. A large number of observations of s under varying load conditions gives rise to a 'probability distribution' of s, $f(s)$, shown in Figure A2.1. The value of $f(s)$ is an indication of the probability that s lies near a particular value. More correctly, the probability that s lies in the interval between s_1 and $s_1 + \delta s$ is given by $f(s_1)\delta s$, the area indicated. The total area under the curve is 1, indicating the total probability that S lies between $+\infty$ and $-\infty$. The mean value, $\bar{s}$ is also indicated in Figure A2.1.

The probability that s lies between S_a and S_b is also indicated on the Figure and is given by:

$$\Pr(S_a < s < S_b) = \int_{S_a}^{S_b} f(s)\,ds$$

The mean value or expected value is thus a measure of the position of the probability density function (pdf) curve $f(s)$. A deterministic evaluation of s for design purposes may be taken as that value of s which is exceeded once every 100 years, ie with a probability of exceedance of 0.01 per year which is the area of the region to the right of S_{100} in Figure A2.2.

The position of S_{100} and its distance from the mean value $\bar{S}$ is determined by the standard deviation of the probability distribution σ_s. The larger σ_s, the greater the spread as shown in Curves 1 and 2 in Figure A2.3. Curve 2 has a larger standard deviation than the more peaked Curve 1. For a normal distribution, that value with 0.01 probability of exceedence is 2.3263 standard deviations above the mean value $\bar{S}$, ie:

$$S_{100} = \bar{S} + 2.3263\,\sigma_s$$

(for a pdf, $f(s)$, representing 1-year maximum values).

The coefficient of variation (COV), C_s, is defined as:

$$C_s = \frac{\sigma_s}{\bar{S}} = \frac{\text{standard deviation}}{\text{mean}}$$

which is a non-dimensional measure of the degree of spread.

The number of standard deviations, E_z by which the observed or chosen value of the random variable s exceeds the mean $\bar{S}$ is a measure of the probability of exceedance of that value (see Table A2.1). A 'confidence level' can be associated with the probability of exceedance of an observed value of s if the probability density or distribution function $f(s)$ and the standard deviation for the distribution are known.

Because the value of the random variable s is commonly the result of a large number of independent contributing factors, the form of $f(s)$ can often be assumed to be the normal distribution given by:

$$f(s) = \frac{1}{\sigma_s\sqrt{2\pi}}\, e^{-\frac{(\bar{S}-s)^2}{2\sigma_s^2}}$$

Other commonly assumed distributions are log-normal, exponential, Wiebull and Rayleigh.

If the normal distribution is assumed then probabilities of exceedance may be associated with a given number of standard deviations from the mean as shown in Table A2.1. For values at 1.6449 standard deviations above the mean, there is a 5% chance of exceedance. The '95% confidence limit' is associated with this value as there is a 95% chance that this value will not be exceeded.

Another useful function in statistical analysis is the cumulative probability distribution function or 'distribution function', F(s). If a function is generated which represents the area under the curve f(s) and to the left of a given value of say S_1, then this function is the cumulative probability distribution function F(s) (see Figure A2.4). The value F(s) is the probability that s is less than (or equal to) an observed value S. If F(s) is the standard normal distribution (with zero mean and unit standard deviation) then this function is written as $\Phi(s)$. In general:

$$F(S_1) = \int_{-\infty}^{S_1} f(s)\,ds$$

A2.2 RELIABILITY THEORY

Consider the load-carrying capacity of a particular member r of an offshore structure (see Figure A2.5). The actual strength of the component may probabilistically be represented by the right hand curve in the figure. The actual load s is also a random variable represented by the left hand curve f(s) plotted on the same axes. The probability of failure, P_f, where the applied load s is greater than the actual capacity or resistance r is 'indicated' by the overlap between the two curves. In fact P_f is given by:

$$P_f = \Pr(r - s \leq 0) = \int_{-\infty}^{\infty} F_r(x)\, f_s(x)\,dx$$

The reliability R, ie the probability that the member will survive the applied load s, is given by:

$$R = 1 - P_f$$

Making the substitution $m = r - s$, the probability of failure is:

$$P_f = \Pr(m \leq 0)$$

If r and s are assumed to be normally distributed, the mean value of m is given by $\overline{M} = \overline{R} - \overline{S}$, its standard deviation is $\sigma_m = \sqrt{(\sigma_r^2 + \sigma_s^2)}$ and it is 'normally distributed', as in Figure A2.6. Then $(m - \overline{m})/\sigma_m$ is distributed according to the standard normal distribution and the probability of failure P_f is given by:

$$P_f = \Pr(m \leq 0) = \Phi\left(\frac{0 - \overline{M}}{\sigma_m}\right)$$

If we now define the reliability index β by $\beta = \overline{M}/\sigma_m$ or $\overline{M} = \sigma_m\beta$ or $\beta = 1/\mathrm{COV}_m$ (the number of standard deviations that the mean of m is above zero), the probability of failure of the component, P_f, is given by:

$$P_f = \Phi(-\beta)$$

The higher β becomes then the smaller the probability that the component will fail. As $\beta = (\overline{R} - \overline{S})/\sqrt{(\sigma_r^2 + \sigma_s^2)}$ it is a non-dimensional measure of the separation of the two probability density functions concerned, of the resistance (r) and load (s) variables.

The partial sensitivity factor, $\partial\beta/\partial S$, is a measure of the rate of change of β with variations of the variable s. Figure A2.7 is a graph of β against S and, clearly, the steeper the curve the more sensitive β is to changes in S. As β may be a function of other variables, the partial differential is used to separate out the effect of a change in any particular variable.

Hence, the probabilistic approach enables us to represent explicitly the degree of uncertainty in a particular resistance or load variable and to attach a probability to the failure of a structural component. The partial sensitivity factor further enables us to identify critical variables which have the major impact on safety and hence serve as a guide to where resources may most effectively be channelled to improve understanding and knowledge. The deterministic approach may be considered to be equivalent to the probabilistic approach with zero standard deviation, mean values only being considered.

In inspection planning, the probabilistic approach enables uncertainties in material properties, loading and the effectiveness of inspection techniques to be taken into account explicitly in the determination of probability of failure of a structural component.

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A2.3 Flint, A R and Baker, M J
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Supplementary report on offshore structures
CIRIA UEG, Report UR9, 1977

Table A2.1: *Normal distribution*

Probability of exceedance	Number of standard deviations above mean
0.500	0
0.150	1.0364
0.022	2.0142
0.001	3.0902
0.05 (5%)	1.6449
0.02 (2%)	2.0537
0.01 (1%)	2.3263

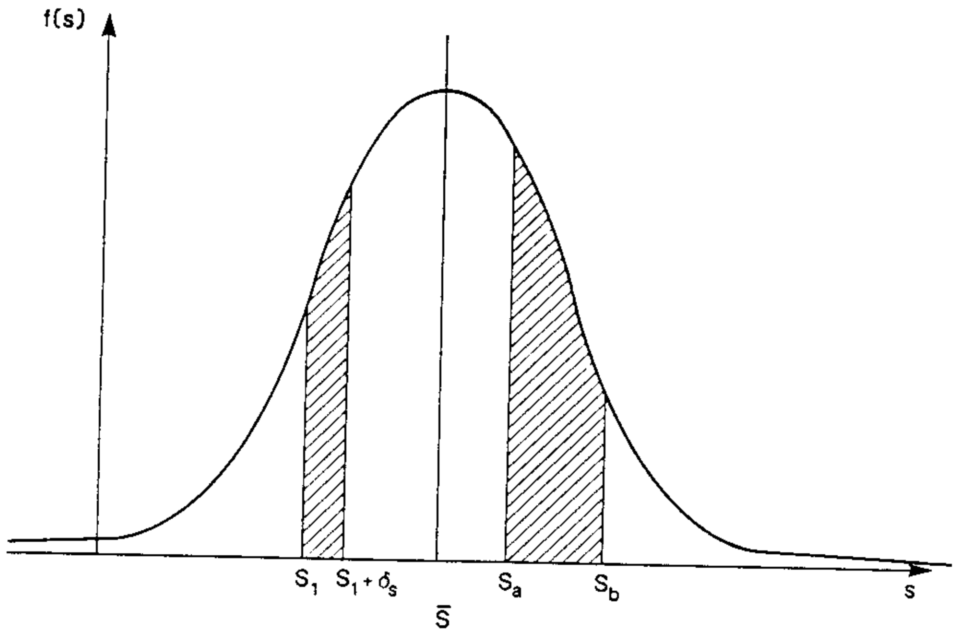

Figure A2.1: *Probability density function, f(s)*

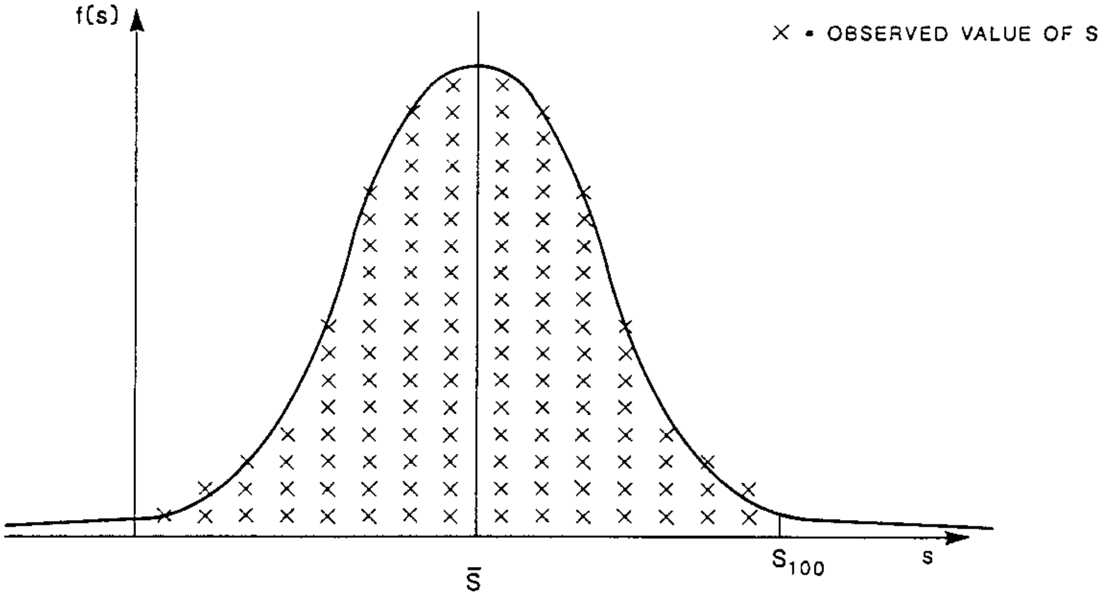

Figure A2.2: *100-year return period design value, S_{100}*

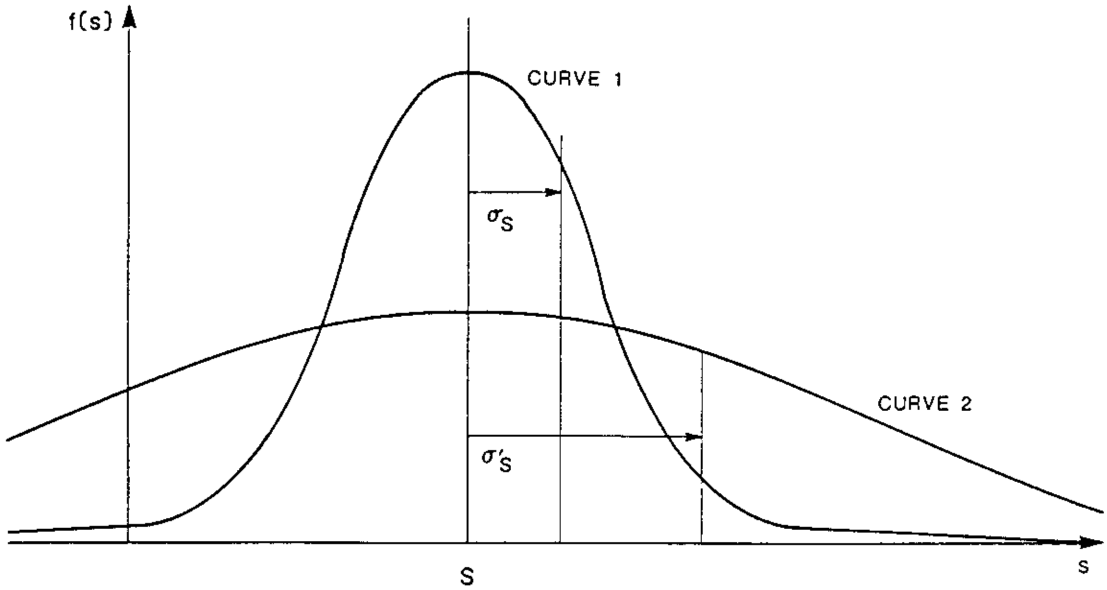

Figure A2.3: *The standard deviation, σ_s*

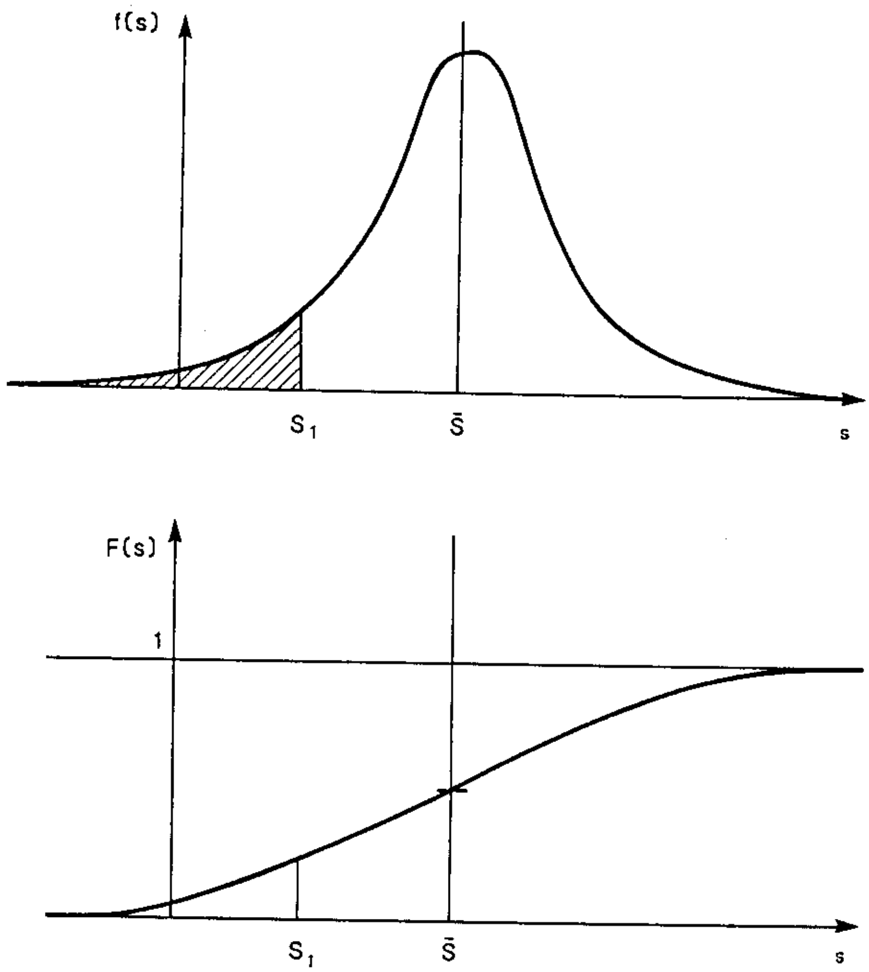

Figure A2.4: *The cumulative probability distribution function, F(s)*

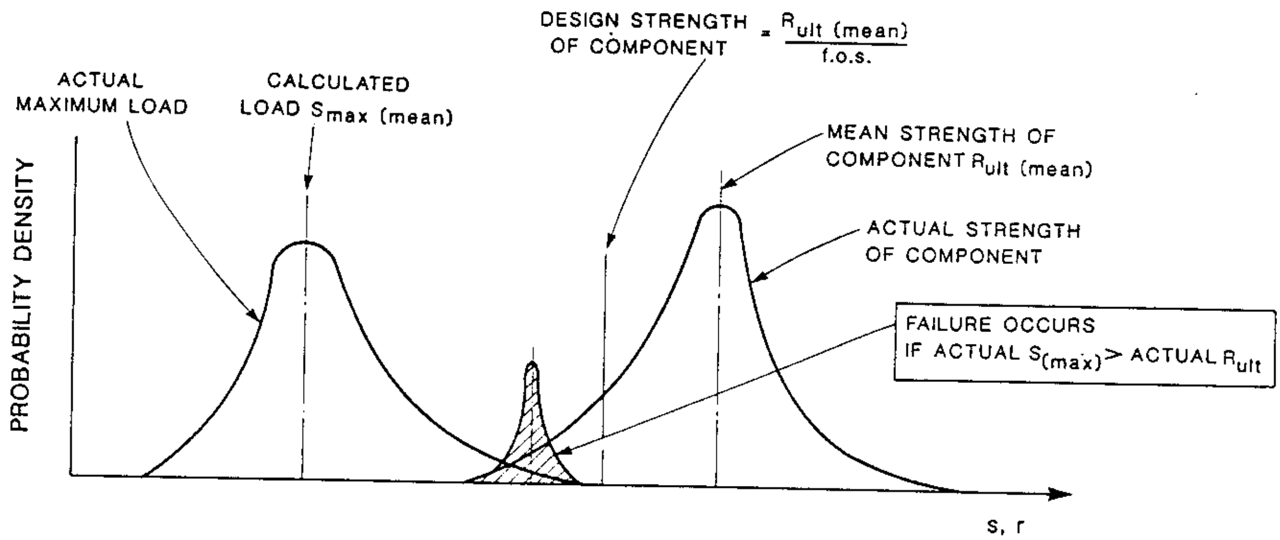

Figure A2.5: *Relationship between load-carrying capacity and load in a component*

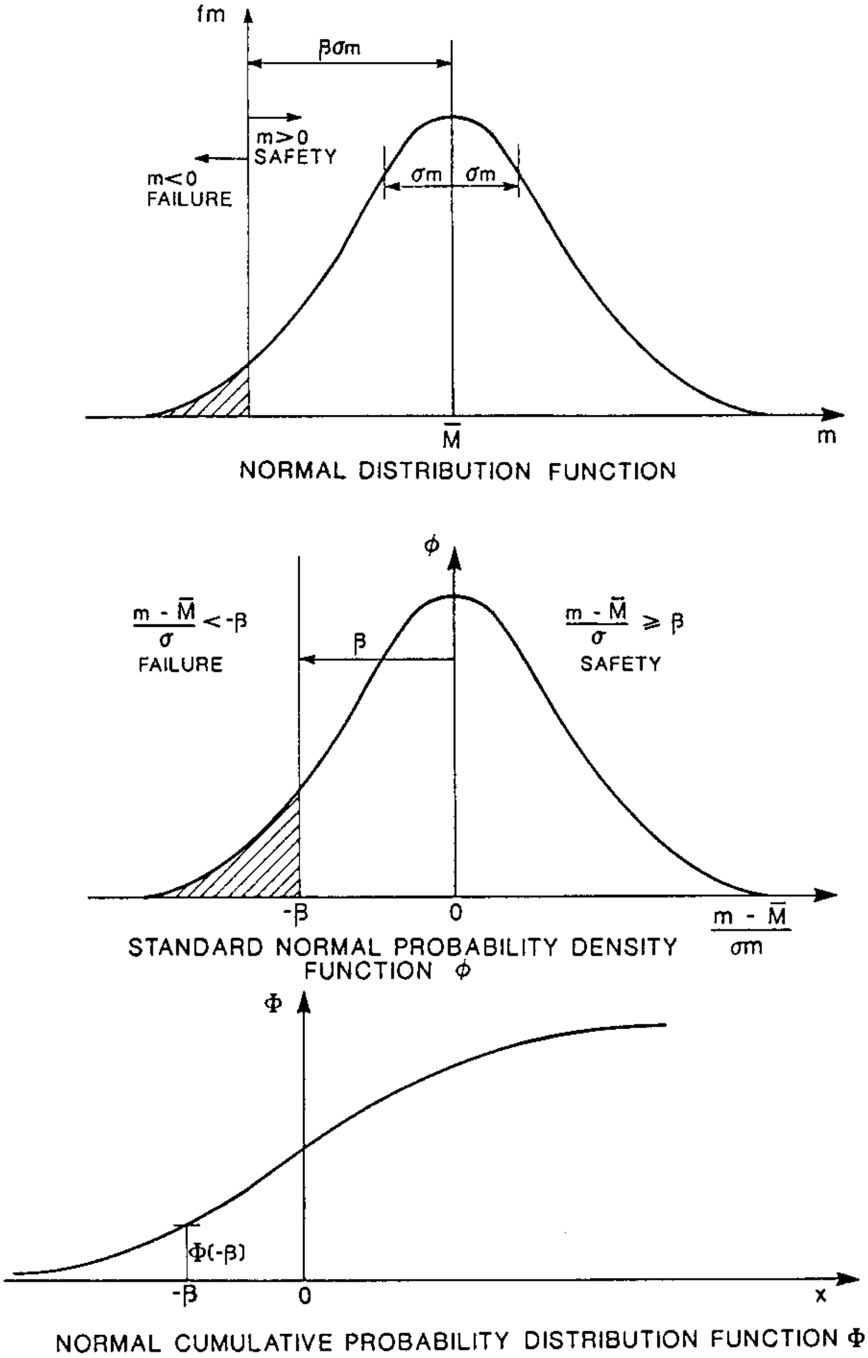

Figure A2.6: *The reliability index, β*

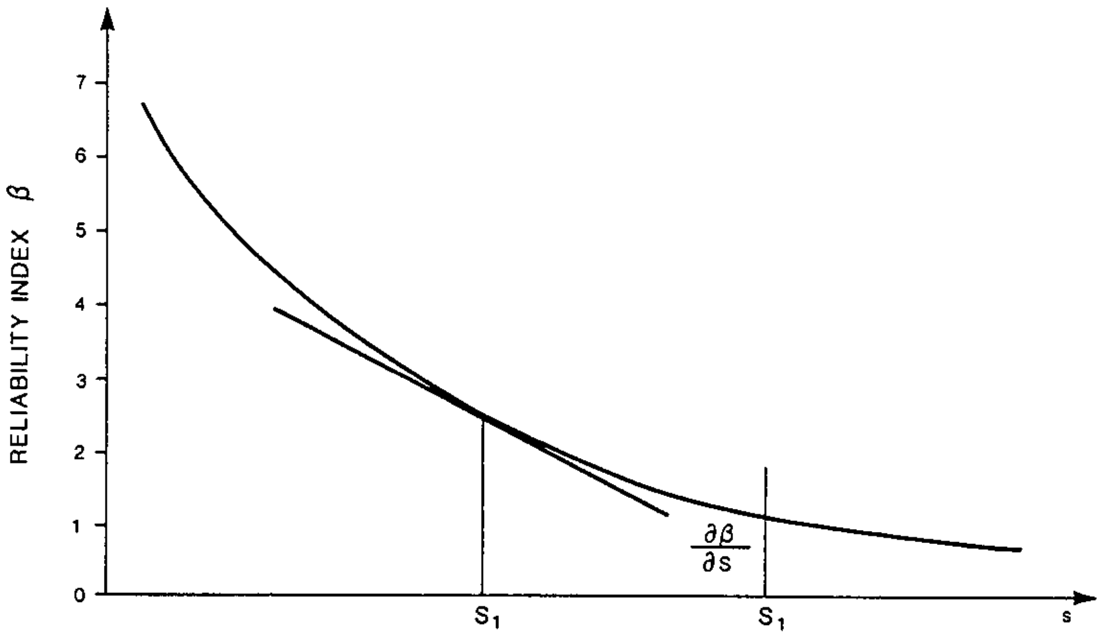

Figure A2.7: *Sensitivity index, ∂β/∂S*

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